Jos. A. Burnley

Dec. 1905

INTERNATIONAL LIBRARY OF TECHNOLOGY

A SERIES OF TEXTBOOKS FOR PERSONS ENGAGED IN THE ENGINEERING PROFESSIONS AND TRADES OR FOR THOSE WHO DESIRE INFORMATION CONCERNING THEM. FULLY ILLUSTRATED AND CONTAINING NUMEROUS PRACTICAL EXAMPLES AND THEIR SOLUTIONS

DYNAMOS AND DYNAMO DESIGN
DIRECT-CURRENT MOTORS
ALTERNATING CURRENTS
ALTERNATORS
ALTERNATING-CURRENT APPARATUS

SCRANTON:
INTERNATIONAL TEXTBOOK COMPANY
12B

PRINTED IN THE UNITED STATES.

//12B
BURR PRINTING HOUSE,
FRANKFORT AND JACOB STREETS,
NEW YORK.

PREFACE

The International Library of Technology is the outgrowth of a large and increasing demand that has arisen for the Reference Libraries of the International Correspondence Schools on the part of those who are not students of the Schools. As the volumes composing this Library are all printed from the same plates used in printing the Reference Libraries above mentioned, a few words are necessary regarding the scope and purpose of the instruction imparted to the students of—and the class of students taught by—these Schools, in order to afford a clear understanding of their salient and unique features.

The only requirement for admission to any of the courses offered by the International Correspondence Schools, is that the applicant shall be able to read the English language and to write it sufficiently well to make his written answers to the questions asked him intelligible. Each course is complete in itself, and no textbooks are required other than those prepared by the Schools for the particular course selected. The students themselves are from every class, trade, and profession and from every country; they are, almost without exception, busily engaged in some vocation, and can spare but little time for study, and that usually outside of their regular working hours. The information desired is such as can be immediately applied in practice, so that the student may be enabled to exchange his present vocation for a more congenial one, or to rise to a higher level in the one he now pursues. Furthermore, he wishes to obtain a good working knowledge of the subjects treated in the shortest time and in the most direct manner possible.

In meeting these requirements, we have produced a set of books that in many respects, and particularly in the general plan followed, are absolutely unique. In the majority of subjects treated the knowledge of mathematics required is limited to the simplest principles of arithmetic and mensuration, and in no case is any greater knowledge of mathematics needed than the simplest elementary principles of algebra, geometry, and trigonometry, with a thorough, practical acquaintance with the use of the logarithmic table. To effect this result, derivations of rules and formulas are omitted, but thorough and complete instructions are given regarding how, when, and under what circumstances any particular rule, formula, or process should be applied; and whenever possible one or more examples, such as would be likely to arise in actual practice—together with their solutions—are given to illustrate and explain its application.

In preparing these textbooks, it has been our constant endeavor to view the matter from the student's standpoint, and to try and anticipate everything that would cause him trouble. The utmost pains have been taken to avoid and correct any and all ambiguous expressions—both those due to faulty rhetoric and those due to insufficiency of statement or explanation. As the best way to make a statement, explanation, or description clear, is to give a picture or a diagram in connection with it, illustrations have been used almost without limit. The illustrations have in all cases been adapted to the requirements of the text, and projections and sections or outline, partially shaded, or full-shaded perspectives, have been used, according to which will best produce the desired results. Half-tones have been used rather sparingly, except in those cases where the general effect is desired rather than the actual details.

It is obvious that books prepared along the lines mentioned must not only be clear and concise beyond anything heretofore attempted, but they must also possess unequaled value for reference purposes. They not only give the maximum of information in a minimum space, but this information is so ingeniously arranged and correlated, and the

indexes are so full and complete, that it can at once be made available to the reader. The numerous examples and explanatory remarks, together with the absence of long demonstrations and abstruse mathematical calculations, are of great assistance in helping one to select the proper formula, method, or process and in teaching him how and when it should be used.

This volume contains an exceptionally clear and complete treatment of the design of direct-current dynamos and motors, together with a detailed discussion of the theory of alternating currents and descriptions of modern alternating-current machinery. In presenting the subject of design, a full discussion of the parts of the machines is first taken up, followed by complete demonstrations of design problems. The subject of armature windings receives special attention. Numerous winding diagrams are provided, indicating clearly the relative positions of the coils, pole pieces, and commutator bars. The text accords with the best modern practice. The theory of the action of motors, their connections and the many systems of speed control are set forth in a clear and comprehensive manner. The importance of a knowledge of alternating currents in the electrical-engineering profession is steadily growing. Illustrations and the graphical methods of treatment have been freely used.

The method of numbering the pages, cuts, articles, etc. is such that each subject or part, when the subject is divided into two or more parts, is complete in itself; hence, in order to make the index intelligible, it was necessary to give each subject or part a number. This number is placed at the top of each page, on the headline, opposite the page number; and to distinguish it from the page number it is preceded by the printer's section mark (§). Consequently, a reference such as § 16, page 26, will be readily found by looking along the inside edges of the headlines until § 16 is found, and then through § 16 until page 26 is found.

International Textbook Company

CONTENTS

ALTERNATING-CURRENT APPARATUS—*Continued*

DYNAMOS AND DYNAMO DESIGN

(PART 1)

THEORY OF THE DYNAMO

INTRODUCTION

1. Principles of Construction.—It has been shown that when an electrical conductor cuts across a magnetic field an E. M. F. is induced in the conductor. If the circuit is completed between the ends of the moving conductor a current will be established as shown in Fig. 1, which current will, in turn, react on the magnetic field and exert a force tending to stop the motion of the conductor—the arrow *a* shows the direction of motion while *b* shows the direction of the reacting force. If we continue to move the conductor against this force, the current will continue to flow, but work must be done to move the conductor against the opposing force; thus it might be said that we have converted dynamic energy into electrical energy, for electrical energy has been obtained at the expense of mechanical effort A machine for generating electrical energy that operates on this principle is called a **dynamo-electric machine** or an **electric generator.** These terms are often abbreviated in **dynamo** and **generator.**

FIG. 1

2. Essential Parts of a Dynamo.—The simplest of all mechanical motions is that of rotation, and dynamos always use this principle for sweeping the conductors through the magnetic field. There are essentially two parts to a dynamo: first, the **field magnet,** wherein is produced the necessary magnetism, and second, the **armature,** on or near whose surface the working conductors are arranged. These two parts are rotated relatively to each other, it being immaterial, except for convenience, which is stationary and which is rotated.

3. It is seldom that a single conductor can be made to generate a desired voltage, so there are usually on an armature a number of conductors that are connected up in series and in parallel, in the same way as electric batteries, until the required voltage and current-carrying capacity are obtained. The subject treating of the methods of interconnecting armature conductors is called *armature windings* and will be treated in detail later.

4. Classes of Dynamos.—Dynamos are divided into two classes according to the character of the current they generate, namely, *direct-current dynamos*, abbreviated D. C., and *alternating-current dynamos*, abbreviated A. C. Direct-current machines deliver currents that are continuous in direction, though perhaps varying in amount as required, while alternating-current machines deliver currents that periodically reverse in direction many times per second. Alternating currents and the dynamos for producing them will be treated separately, the present section being confined to direct-current dynamos.

5. The direct-current dynamo necessarily has a stationary field magnet and a revolving armature. The reason for this is that the brushes that collect the current generated in the armature must keep a fixed position with respect to the poles of the field magnet; and since these brushes require occasional adjustment it is best that they remain stationary, hence the field-magnet poles must also be stationary.

6. The field magnet may be either a permanent magnet or an electromagnet; but except for very small dynamos, electromagnets are necessary because they are more powerful and because it is practically impossible to construct and harden large masses of steel of a kind suitable for permanent magnets. Whère the field is produced by electromagnets, the exciting coils are usually supplied with current generated by the dynamo's own armature; such a machine is termed a **self-excited dynamo.** Where an outside source of current is resorted to for excitation the machine is called a **separately-excited** dynamo.

Quite a number of shapes and styles of field magnets have been successfully used commercially, and will be discussed later. Like other magnets, there must be a complete magnetic circuit, but for the purpose of the following discussion only the armature and pole pieces will be considered, the remainder of the magnetic circuit being for the present omitted.

ACTION OF THE ARMATURE

7. In Fig. 2 is shown an end view of the pole pieces *N* and *S* of a field magnet, while between them is shown an

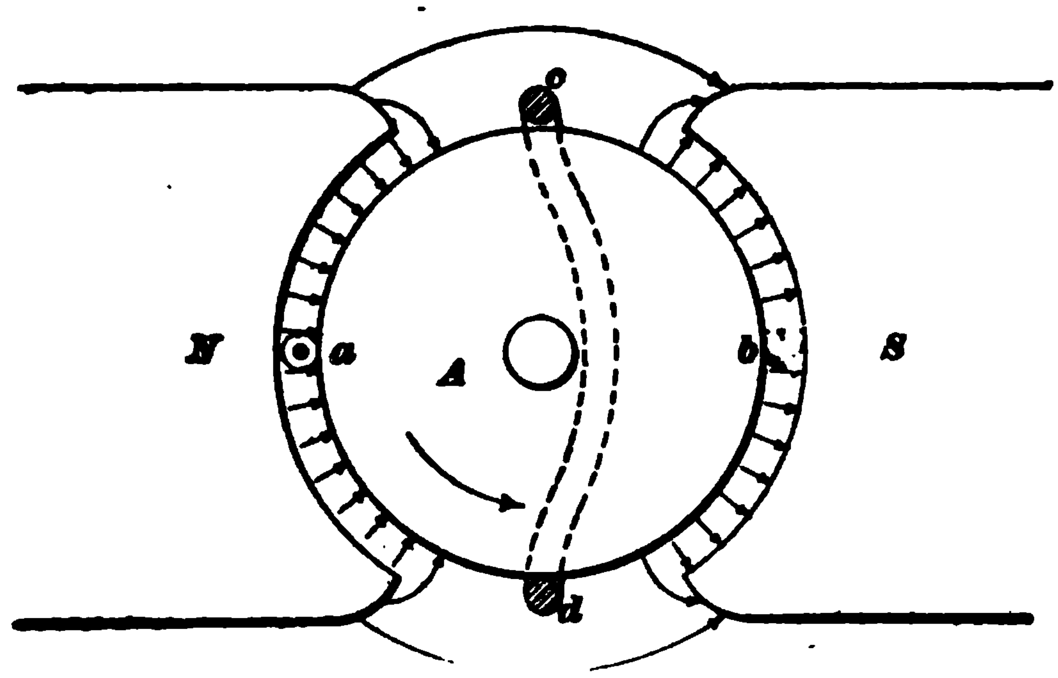


FIG. 2

armature core *A* of soft wrought iron mounted on a suitable shaft and capable of being rotated. This wrought-iron

armature core being of high magnetic permeability serves to convey or conduct the magnetic induction or magnetic flux from pole to pole, greatly reducing the magnetic reluctance of the path. The space between the core and the poles is called the **air gap.** This space is often occupied with insulation, copper wires, etc., but since these substances have practically the same permeability as air, the complete region from pole to armature core is referred to as the air gap, regardless of whatever may intervene, so long as it is not iron.

It will be seen that a conductor *c* attached to this armature core and revolved with it in the direction indicated, will cut across all the magnetic induction either entering or leaving the core, and, consequently, will have an E. M. F. induced in it. Applying the rule for determining the direction of the induced E. M. F., it will be found that when the conductor is under a north pole, as at *a*, the E. M. F. is upwards from the paper, while when it is under the south pole it is downwards. If the direction of rotation were reversed, the E. M. F. would be upwards under the south pole and downwards under the north. In all the diagrams relating to dynamos or motors, an up-flowing current, that is, a current flowing up through the plane of the paper, will be represented by a dot in the center of the wire as at *a*; down-flowing currents will be represented as at *b*, the wire being filled in black.

It will be noticed that the wrought-iron core need not be rotated in order that the conductor may be caused to generate an E. M. F., but no serious difficulty is encountered in so doing, and it is very convenient to support the conductors by attaching them firmly to the core and rotating the whole.

8. In the conductor *c*, Fig. 2, there is induced an E. M. F. that alternates in direction every half revolution; such an E. M. F. is called an **alternating** E. M. F., and would induce an alternating current were the circuit completed between the ends of the conductor.

Suppose another conductor *d* were also attached to the core diametrically opposite to *c*. It also would have E. M. F.'s induced in it in the same manner as *c*; but, being on opposite sides when the E. M. F. of one was upwards, that of the other conductor would be downwards, and vice versa. These two conductors could then be connected together at

FIG. 3

one end of the armature, as in Fig. 3, without having their E. M. F.'s interfere or at any time oppose one another so that at the ends of the loop, or turn, the sum of the two induced E. M. F.'s would be impressed.

9. Elementary Alternating-Current Generator.—In Fig. 3 the ends of the loop are shown as terminating in two metal rings insulated from each other and from the shaft. Upon these **collector rings** *g*, *h*, as they are called, rub two metal **brushes** *e*, *f* that serve to collect the current generated in the armature wires and make it available for the outside circuit *R*. The E. M. F. impressed on the circuit *R* is still an alternating E. M. F., since the brushes make permanent, though sliding, connection with the loop *c*, *d*; hence, the current that flows through *R* will be an alternating current. In fact, Fig. 3 represents an elementary alternating-current generator.

10. In Fig. 4, a curve is plotted that shows the relation between the E. M. F. and the time required for a revolution, using the volts between the brushes *e*, *f* as ordinates and the time in seconds as abscissas. Starting with the

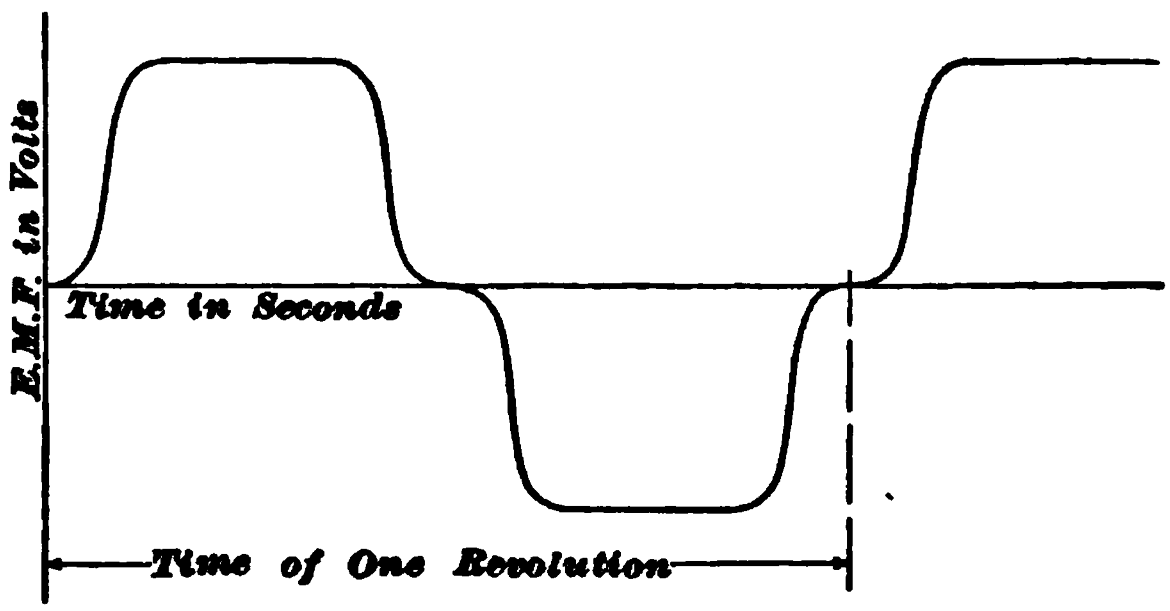


FIG. 4

loop in a position midway between the poles, there is no E. M. F. developed, since no cutting takes place until the face conductors pass beneath the pole faces. As the coil passes under the poles, the E. M. F. rises, reaching a maximum and remaining there until the loop again passes out between the poles, when the E. M. F. falls to zero and later rises in the reverse direction, etc., as shown in Fig. 4. One positive wave, represented above the axis, and one negative wave of E. M. F., represented below the axis, are developed every revolution. It should be noted that the shape of the curve in Fig. 4 depends on the distribution of the magnetic field around the armature.

11. Suppose the collector rings *g*, *h*, Fig. 3, were replaced by a single ring split into two semicircles, the halves being connected, each to an end of the loop, as in Fig. 5, but insulated from the shaft and from each other. A current of entirely different character would now be collected by the brushes *e*, *f*, for as the loop revolves so also does the split ring, and the brushes and split ring are so arranged that, at the instant when the E. M. F. induced in the loop reverses, the brushes reverse their connections to the loop by sliding from

one-half of the split ring to the other. In this way the E. M. F. at the brushes will not reverse at each half revolution, although the E. M. F. induced in the loop is alternating

FIG. 5

as before. In Fig. 6 is shown the corresponding E. M. F. time curve. Comparing it with the curve in Fig. 4, it will be noted that they are the same, except every alternate wave

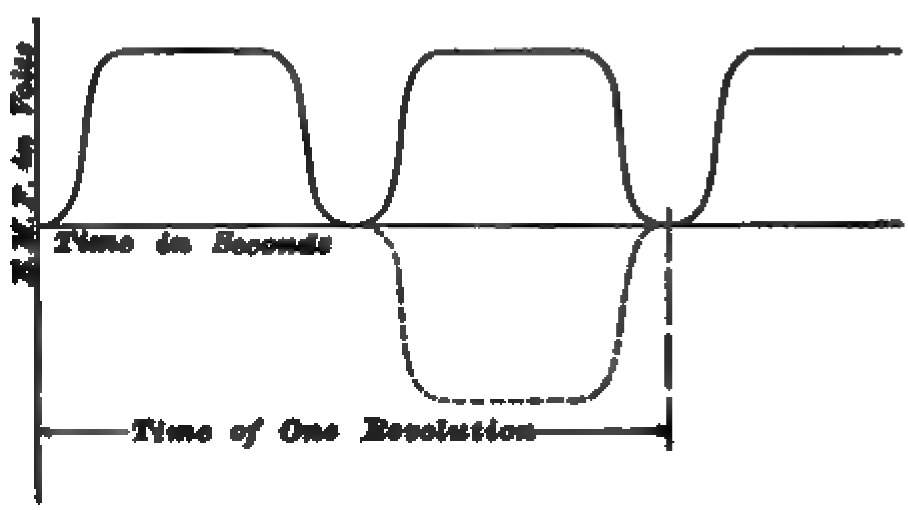


FIG. 6

has been reversed in direction by the rotation of the split ring and the consequent change of connection with the outside circuit R.

12. An E. M. F. like that plotted in Fig. 6, since it does not alternate in direction, is called a **direct** E. M. F., but on account of its variable character it is usually termed a **pulsating** E. M. F. The variations are due entirely to the fact that there is but a single loop on the armature of Fig. 5, which, from the nature of the case, cannot always be generating. The E. M. F. may be made quite uniform by using several loops instead of one, connecting them up after

Fig. 7

the manner of Fig. 7. This shows two loops connected to a ring split into four segments. The armature core and shaft are omitted in order to make the windings more distinct. The loop $m\,m'$ terminates in the opposite segments a, a, while the loop $n\,n'$ terminates in the segments b, b'.

13. The action of the two-loop armature in smoothing out the pulsations is as follows: When the face conductors

of one loop, which has been active, nears the edges of the pole pieces where its E. M. F. will fall off, the segments to which it is connected slide from under the brushes and the loop is cut out of circuit; at the same time the other loop, which is just approaching the most active position, is cut into the circuit, maintaining the E. M. F. during the inactivity of the first coil and carrying whatever current the dynamo is generating until it, in turn, is cut out, and so on. The loops are only in the circuit while they are in active positions, so that the E. M. F. cannot fall much in the outside circuit, and the pulsations are therefore greatly reduced. In Fig. 7, $+B$ and $-B$ are the brushes and *Re.* the external circuit to which the armature supplies current, as indicated by the ammeter *A. M.*

14. Commutator.—The split ring is called the **commutator,** and it is the essential and distinctive feature of the direct-current dynamo, for it is by its use that the alternating E. M. F.'s developed in the armature windings are rectified, or commuted into direct E. M. F.'s. In most modern generators the commutators have a great many segments.

If a single loop or turn of wire, as shown in Figs. 5 or 7, does not develop the required E. M. F., more turns may be added, and each additional turn adds two active conductors in series with the others. If all the turns of a coil are wound approximately in the same plane, the E. M. F.'s of all face conductors will rise and fall together, so that the action of what has now become a coil is identical with that described for a single loop, except that the E. M. F.'s are increased in proportion to the number of turns in the coil. Diagrams of windings, then, like Figs. 5 or 7, may be considered as having coils of many turns instead of one, with the ends of the coils terminating in segments as shown for the single turn, and in many of the diagrams to be given later it will be understood that where but a single turn per coil is shown for simplicity, many turns per coil will have identically the same action.

15. Drum and Ring Armatures.—Windings made after the manner of Figs. 5 or 7 are called **drum windings**, on account of the armature core being of a drum form, and an armature thus wound is called a **drum-wound armature**, or a **drum armature**. Another type of windings not nearly so generally used is wound on a core made into the form of a ring with the windings threaded through the ring, as shown in Fig. 8. It will be seen that where more than one turn is put on, as in Fig. 8, that the E. M. F.'s developed will be in series exactly as are the E. M. F.'s on the two sides of the loop in Fig. 3.

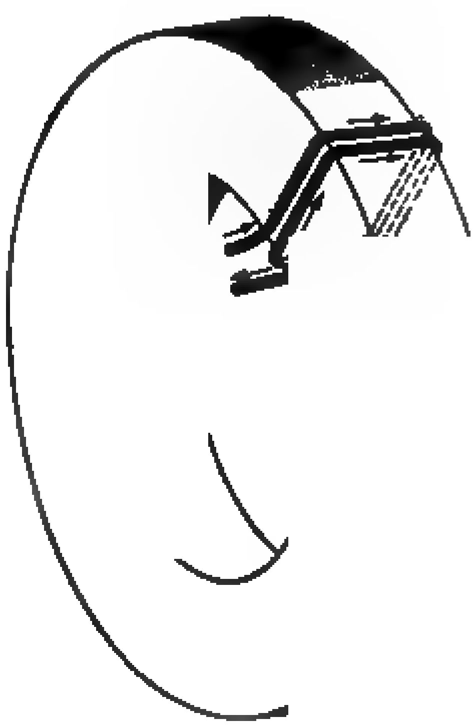


FIG. 8

16. Inductors, or Face Conductors.—Fig. 9 represents the magnetic flux around a ring-wound armature. It

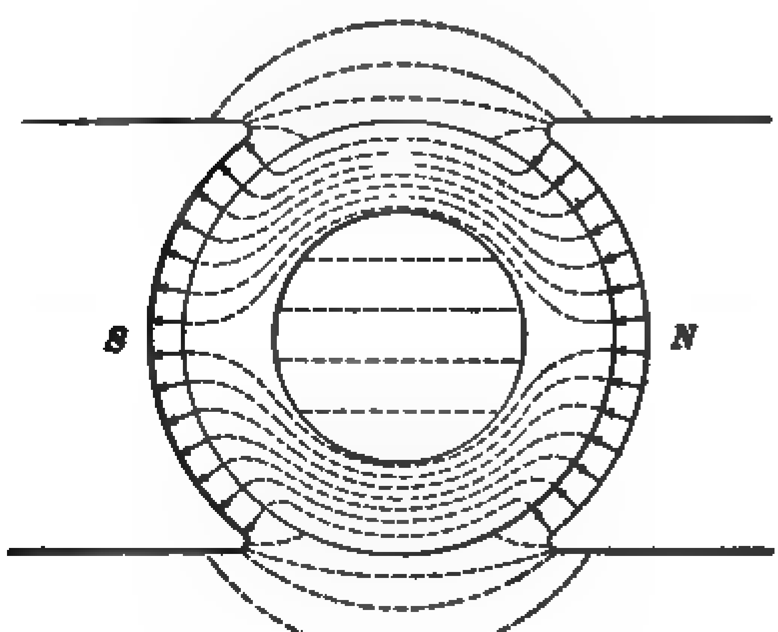


FIG. 9

will be noticed that but a small field is found in the middle of the ring, so that, as in the case of the drum winding, the

part of the conductor that generates the E. M. F. is the part that is on the outside of the ring and sweeps under the poles. This part of a conductor is usually termed an **inductor,** or a **face conductor.** It is evident that a face conductor on a ring core will develop the same E. M. F. as one on a drum core, where the total induction or flux from one pole to the other is the same and where the speed is the same. Thus, the coil of two turns in Fig. 8 is exactly equivalent to one loop or turn in Fig. 7, so far as the generation of an E. M. F. is concerned, since in each case there are two face conductors in series.

Fig. 10 shows a ring winding exactly equivalent, electrically, to the drum winding of Fig. 7, except that it will

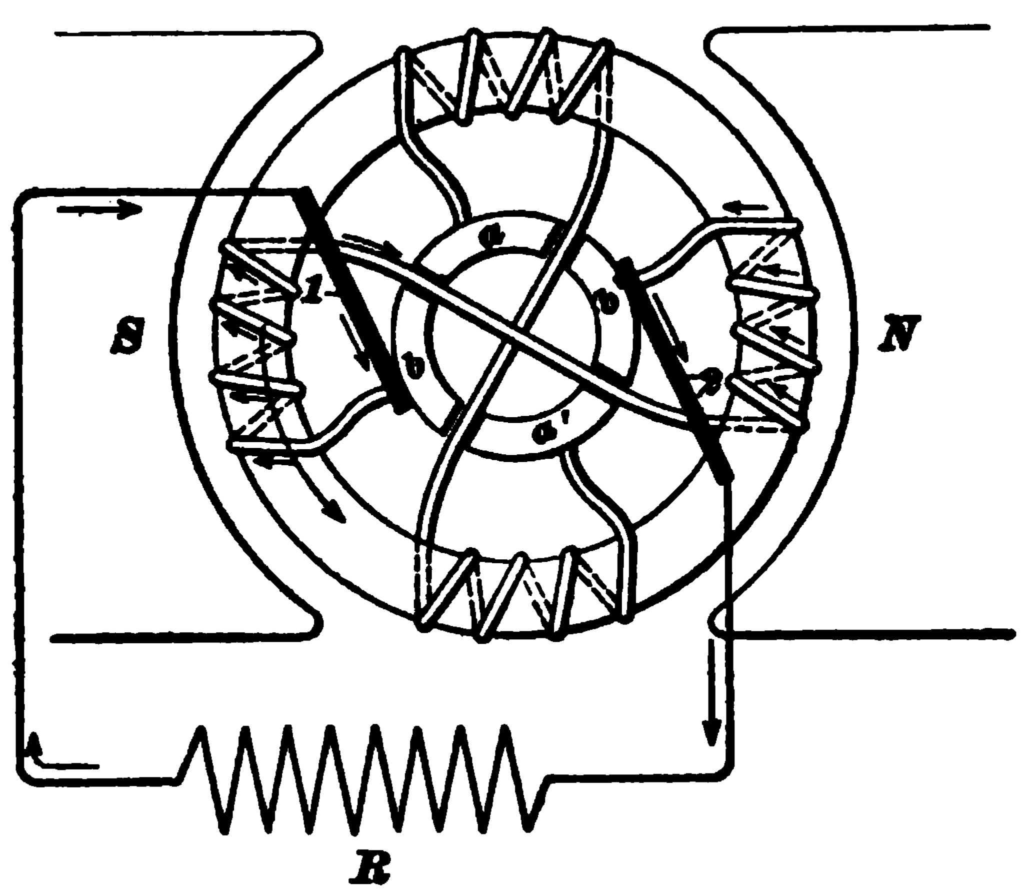


FIG. 10

develop four times the voltage of Fig. 7, at the same speed, because it has four times as many face conductors in series between opposite commutator segments.

17. Open-Coil and Closed-Coil Windings.—The windings shown in Figs. 5, 7, and 10 are known as **open-coil windings,** from the manner in which they are connected to the commutator. Another type, the **closed coil,** which is far more used, is shown in diagram in Fig. 11. This shows a ring wound continuously by a conductor whose

ends are joined, thus forming a closed winding, whence the name. As the armature revolves, conductor *a* has an E. M. F. induced in it which is added to that of *b*, *c*, *d*, and *g*, because they are all connected in series, and the difference of potential between the points *x* and *y* is the sum of the E. M. F.'s developed in all the conductors under the *N* pole. In the same way, between *o* and *p* is the sum of the E. M. F.'s developed under the *S* pole, and since these poles are of the same strength and size, and since the conductors are evenly spaced, there are as many conductors from *x* to *y* as from *o* to *p* and the E. M. F. between *x* and *y* is equal to

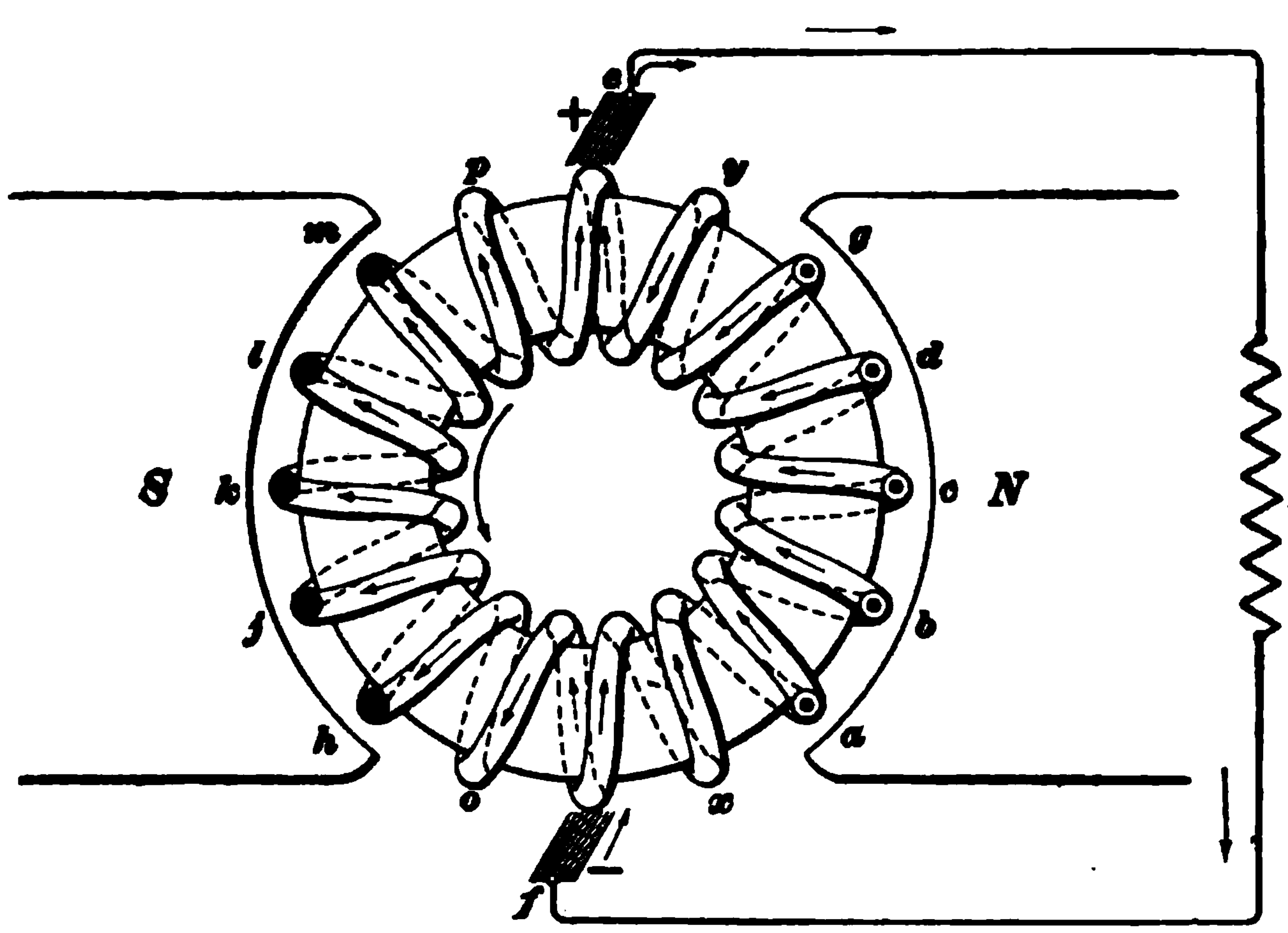


FIG. 11

that between *o* and *p*. It will be noticed that these two induced E. M. F.'s are opposed to each other in the windings and, being exactly equal, no current can be produced in the armature itself; but if a pair of brushes *e*, *f* are arranged so that they will rub on the conductors as they pass what is termed the **neutral region** between the poles, *e* will be at the same potential as *p* and *y*, and *f* at the potential of *o* and *x*, and if a circuit *R* is completed between these brushes, a current will be set up. Notice that, within the armature, the current divides as shown by the arrows; it

would be said of this armature winding that there are two circuits, or paths, from positive to negative brushes. As the armature revolves, the conductors successively come in contact with the brushes, but the number of conductors under each pole (on which the E. M. F. between the brushes depends, assuming the total flux and the speed to remain the same) remains always about the same, so that the E. M. F. will remain constant and the action will be continuous.

It is not always convenient or possible to have the brushes rub on the conductors themselves, and the winding is therefore, in nearly every case, connected to a commutator as shown in Fig. 12.

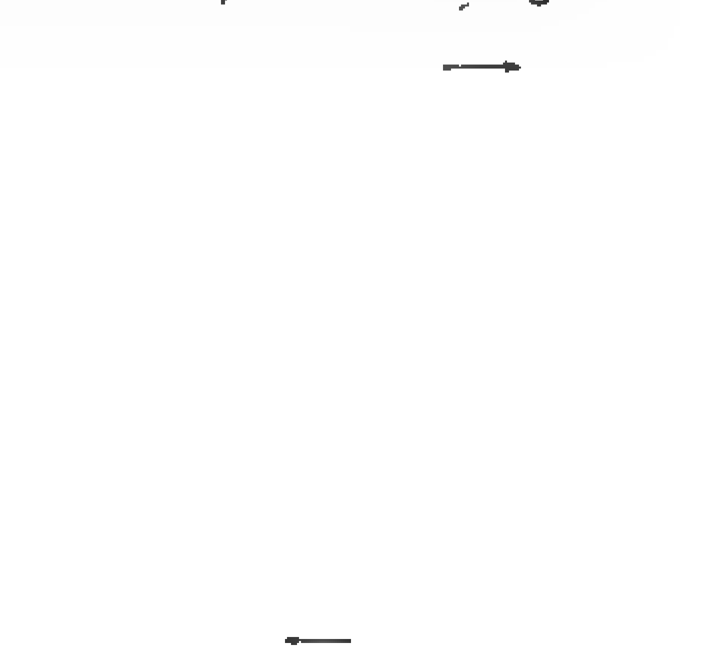


FIG. 12

18. Diagrams Figs. 10 and 12 are typical of ring-wound open-coil and closed-coil windings, respectively, and should be carefully compared. Notice that the ends of a coil in Fig. 10 terminate in segments on opposite sides of the commutator, while in Fig. 12 the ends of a coil connect to adjacent commutator segments. Also, in Fig. 10, the brushes are in connection with a coil when it is under the poles, while in Fig. 12 the brushes are only in contact with a coil when it is in the neutral region.

19. Commutation.—Consider the coil *b* in Fig. 12. It will be noticed that it is short-circuited, at the instant shown, by the brush *e* touching both segments in which the coil terminates. The coil *a* to the right of it has the current flowing through it to the left, while that to the left *c* has the current flowing through it to the right. As the coils are continually passing from right to left as the

armature revolves, the current in each must be reversed as it passes the brush. In a closed-coil winding, then, as the segments in which a coil terminates pass a brush, the coil is short-circuited for a short interval, and, further, the direction of the current in it is reversed. This action is termed **commutation**, and coil *b* is said to be *under commutation* at the instant shown.

In Fig. 13 is shown a drum-wound closed-coil type of armature winding with 8 coils, each having two face con-

FIG. 13

ductors. These coils have their ends terminating in adjacent commutator segments; hence, it is a winding similar in action to Fig. 12. In fact, Fig. 13 is, electrically, exactly equivalent to Fig. 12, except that the drum type of coil is used in one and the ring in the other. They would generate exactly the same voltage if run at the same speed with the same magnetic induction from pole to armature, because both have the same number of face conductors per coil and the same number of coils. In the diagram, the connections across the rear end of the core between conductors are omitted in order not to confuse the figure. A conductor on one side does not connect to the one diametrically opposite

it, but lacks one conductor of doing so, thus forming what is sometimes called a **chord winding.** The turn connects across a chord instead of a diameter, thus making the turn slightly shorter and avoiding the armature shaft to better advantage. Drum armature windings will be taken up in detail in connection with the subject of armature windings.

20. Armatures are said to be drum armatures when supplied with a drum type of winding and ring armatures when supplied with a ring type of winding, regardless of the shape of the armature core. Almost all modern machines use armature cores that are of the ring shape because these machines have armatures of large diameter and short length, but if the winding does not thread through the center of the ring it is a drum winding and the armature is called a drum armature.

GENERAL FEATURES

21. Multipolar Field Magnets.—Dynamos whose field magnets have but a single pair of poles are called **bipolar dynamos,** while those with more than one pair of poles are called **multipolar.** In multipolar machines the poles always alternate north and south, as in Fig. 14, so that it is necessary to have as many north as south poles, consequently there is always an even number of poles.

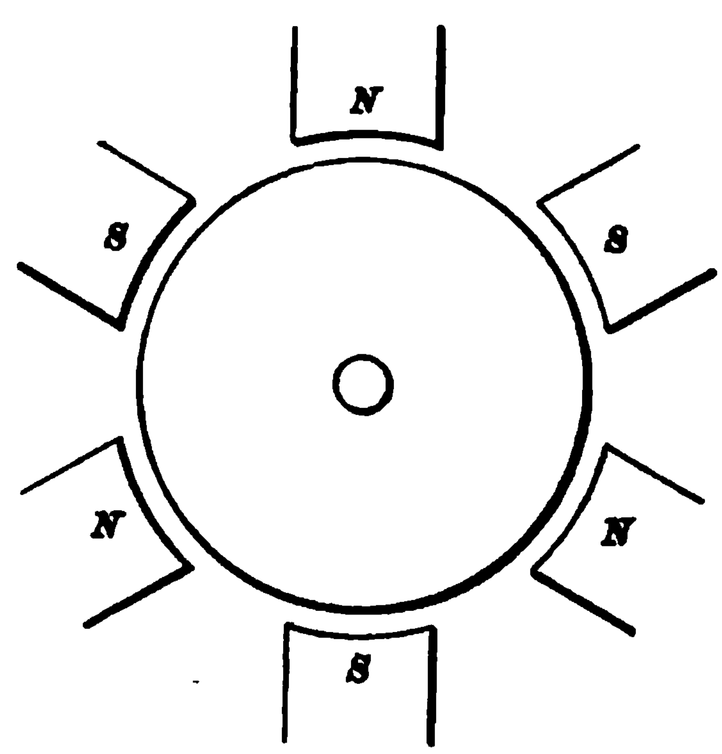


FIG. 14

22. Direct-Driven and Belt-Driven Dynamos.—Dynamos, like any other kind of machinery, are driven by steam engines or waterwheels and may either be connected by a belt and pulley or may be direct connected to the prime mover. The former are termed **belted dynamos** and the latter, where the armature is intended to be mounted on an extension of the shaft of a

pe.

af
or

Fig. 16

steam engine, are termed **direct-driven** or **engine type.** The former type usually run at higher speeds than the latter, but otherwise the two classes of machines are identical.

Fig. 15

Fig. 15 shows a modern belted dynamo. *A* is the circular yoke of the field magnet, which is made in two pieces for

FIG. 16

convenience in building and repairing. The pole pieces project inwards from A and are surrounded by the magnetizing coils B, termed the **field coils.** The armature H revolves within the poles, being supported by a shaft that also carries the pulley for driving. The armature windings may be seen terminating in the segments of the commutator C, on whose surface rub the brushes M, which serve to collect the current. The devices for holding the brushes are called **brush holders,** and these are supported on an insulated stud N securely fastened to the **rocker-arm** K. The brushes require occasional adjustment and the rocker-arm is capable of rotating through a small angle, the movement being controlled by a worm-gear, not shown, connected to the hand wheel J.

The shaft is supported by three pedestals G, which contain the bearings and their oiling devices. The bedplate F to which the pedestals are bolted is supported on rails R, two of which are provided with screw devices for sliding the complete dynamo for the purpose of varying the tension on the driving belt. Fig. 16 shows a comparatively small direct-driven dynamo. The dynamo bedplate A is practically an extension of the engine bedplate. The armature M is mounted on the engine shaft; C, D are the terminals of the machine and W the hand wheel for regulating the brushes.

ARMATURE-CORE LOSSES AND TOOTHED ARMATURES

23. Eddy-Current Loss.—Thus far armature cores have been considered as made of a solid mass of soft wrought iron, having the conductors forming the winding attached to the surface. Some of the early dynamos were thus constructed but they were found to be inefficient on account of currents being induced in the iron core itself as well as in the conductors. These currents circulating in the mass of iron caused the core to heat on account of the resistance offered to the currents. They are called **eddy currents** and the loss they entail is called the **eddy-current loss.**

The E. M. F. producing these eddy currents is necessarily low, but if the core is a solid mass of metal the resistance offered is extremely small and the small E. M. F. will cause enormous currents to flow. The direction of these currents near the pole surface is the same as those induced in any other conductor and the currents circulate as shown in Fig. 17, which shows half of an armature core only, with the direction of the eddy currents marked on the section.

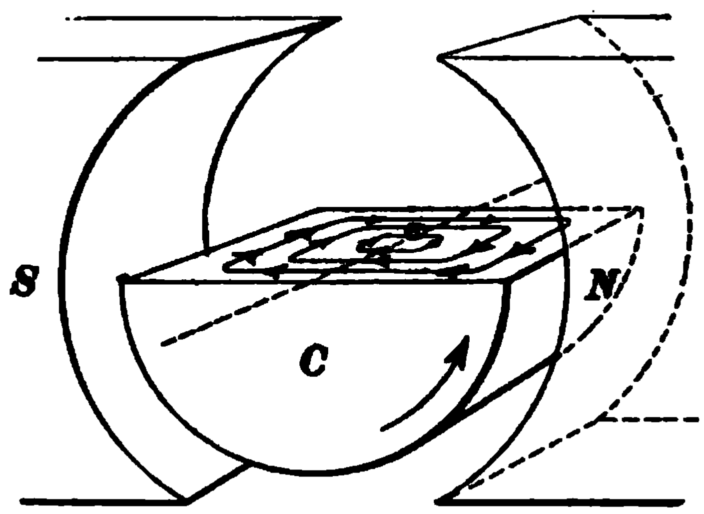


FIG. 17

To reduce the eddy currents and thus prevent the losses they entail, armature cores are built up of a number of thin iron disks from .01 inch to .06 inch thick, as shown in Fig. 18, arranged parallel to the lines of force and perpendicular to the axis of rotation. These disks are insulated from one another, and the length of conductor parallel to the shaft being reduced to a small fraction of an inch reduces the magnetic flux cut to a very small value of what it would be were there several inches of solid conductor; hence, the rate of cutting and the E. M. F. tending to set up eddy currents is greatly reduced. Further, the resistance offered to the flow of these currents is so increased that the currents themselves are doubly reduced.

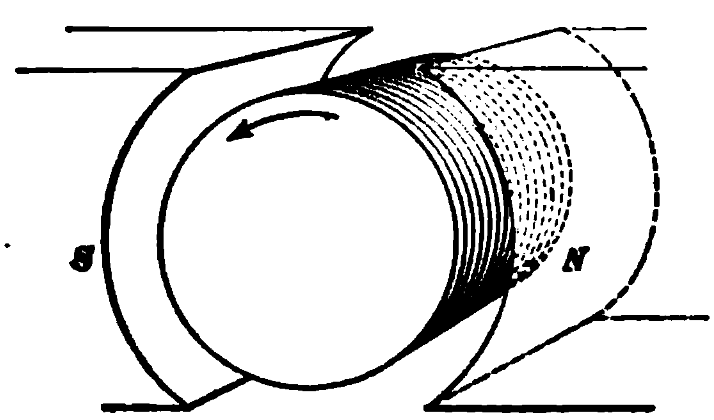


FIG. 18

This process of dividing the core into thin plane sections is called **lamination,** the separate sections forming the **laminæ.** Lamination does not affect the magnetic qualities of the core, since all the sections are continuous in the direction of the lines of force.

Building up the core of lightly insulated iron wire will also prevent eddy currents, but as in this case the iron of the core is not magnetically continuous, the reluctance of

the core as a whole is much greater than that of the iron of which it is composed. The laminated structure is therefore used almost exclusively.

24. Hysteresis Loss.—Revolving the armature core in the magnetic field entails still another loss of energy due to **magnetic hysteresis.** Hysteresis is due to the continual change in the direction of the lines of force through the core as it rotates, amounting to one complete reversal in each half revolution in a bipolar machine. The amount of the hysteresis loss depends on the quality of the iron of which the core is made, the density of the lines of force in the core, the number of reversals of the magnetism per second, and the amount of the iron affected.

25. The chief reluctance of the magnetic circuit of a well-designed dynamo is at the air gaps, and in order to reduce this to a minimum the conductors are usually laid in slots, or even in holes near the surface, so that the iron of the core approaches very nearly to that of the pole pieces. Armature cores where the windings are so made are termed **slotted,** or **toothed, armatures** and **perforated armatures,** respectively, while if surface windings are used they are called **smooth-core armatures.** One of the advantages to be gained by laying the windings in slots is that the conductors and their insulations are thus thoroughly protected from injury.

CLOSED-COIL ARMATURE WINDINGS

26. Closed-coil armature windings usually consist of a large number of coils connected up to a commutator with many segments. These coils may consist of one or of many turns, according to the requirements and may be either drum or ring wound. It should be understood that the manner of winding the coils is entirely separate and distinct from the manner of connecting them to the commutator. Windings differ very much in their properties according to the method of interconnecting the coils with the commutator.

27. The coil is the natural unit of the winding and for the present purpose may be defined thus: If we start at any commutator segment and follow a conductor connected thereto around through its convolutions on the armature until we arrive at another segment, we will have traversed a coil.

MANNER OF WINDING THE COILS

28. Pitch, or Spread, of Coils.—As has already been stated, the drum type of coil is by far the most used. In Fig. 19 is shown a drum-wound coil in a multipolar field. The sides of the coil *a* and *b* should be separated by about the same angle *c* as the angle between adjacent poles *d* in order that the conductors at *a* may pass under and out from the poles simultaneously with the conductors at *b*. The angle *c* is often referred to as the **angular pitch,** or **spread, of the coils,** and the angle *d*, which is the

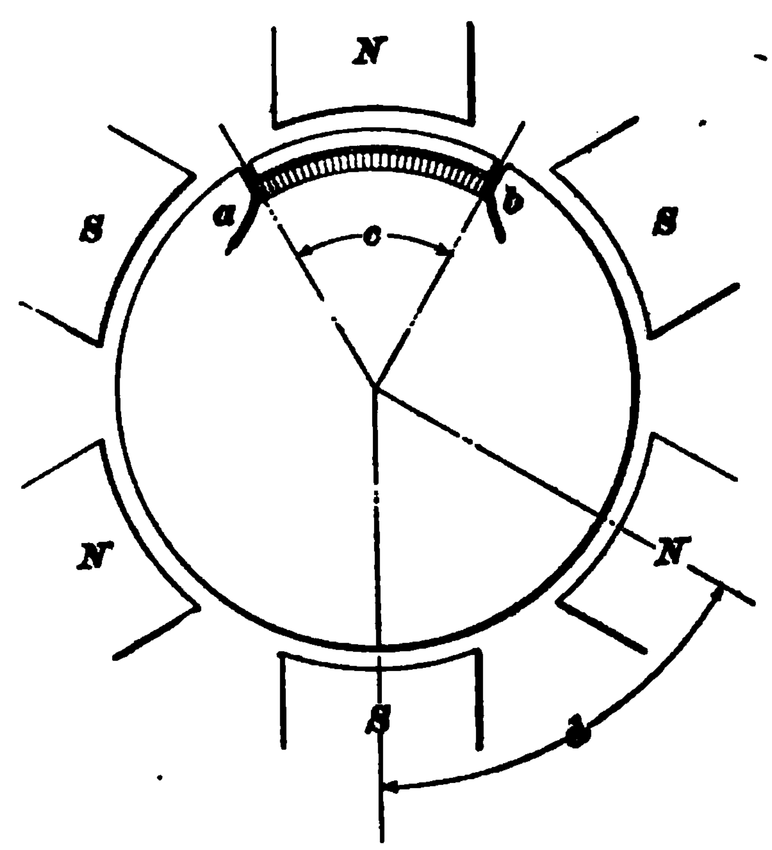


FIG. 19

angle between corresponding points on adjacent poles, as the **angular pitch of the poles.** The angular pole pitch in a bipolar machine is 180°, in a four-pole machine 90°, etc. The spread of the coils may differ a little from the angular pole pitch without affecting the action of the machine, but if the difference is large the coil will not commutate properly. This is because the coil is short-circuited by a brush during commutation and this should take place only when the coil is not developing any E. M. F., that is to say when both sides are in the neutral region between the poles. Now it will be seen on consideration that with poles of a given size, the angle through which the armature and coil can turn

while both sides remain in the neutral region is greatest when the spread of the coils is equal to the pole pitch.

On most armatures there are a large number of coils that overlap one another considerably. On account of sparking at the commutator, it is very desirable that all armature coils should be alike; this is especially desirable with multipolar armatures. If a coil were wound and then another over it, and so on, the first coil, being underneath, would be much shorter than the last one at the top. This would cause unequal division of the currents through the paths, or circuits, in the armature and unequal heating due to different resistances on the various paths. In order to avoid this trouble, multipolar drum windings are usually made up of coils formed on a frame into such shapes as will nest together and are afterwards assembled on the core.

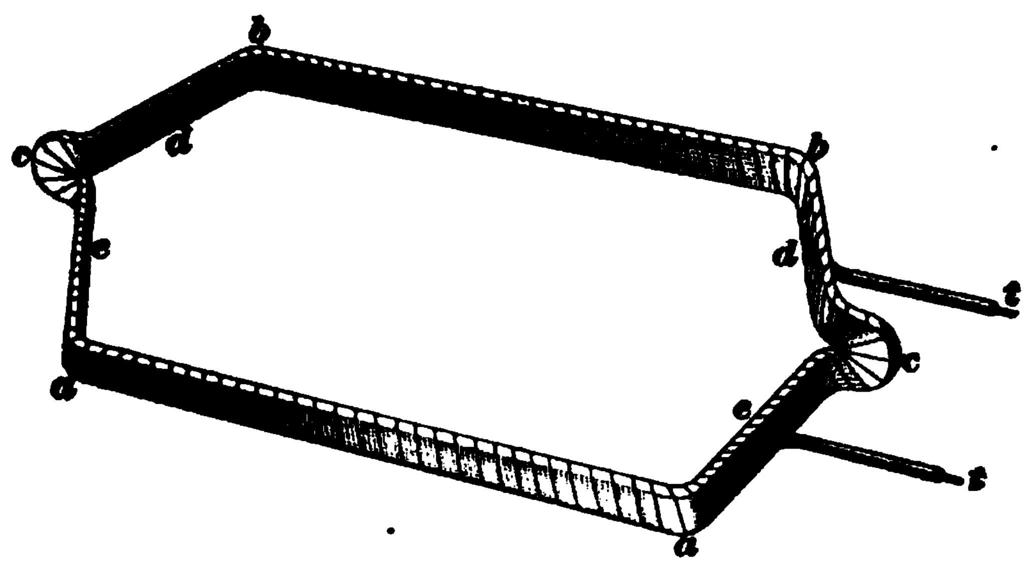


FIG. 20

29. Shape of Coils.—There are two chief methods of making these coils, both of which are practically alike, a

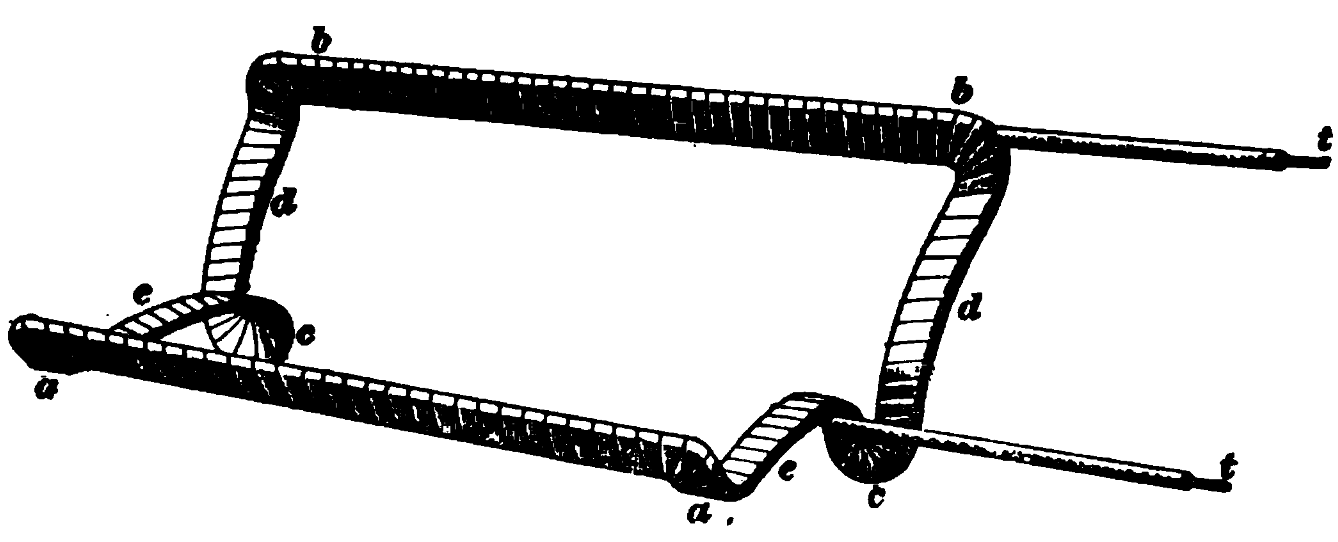


FIG. 21

typical coil of each is shown in Figs. 20 and 21. The

parts *a a* and *b b* are composed of the face conductors and lie in the slots, the parts *d*, *e* are termed the end connections and project beyond the armature core. The terminals *t*, *t*, termed the **leads** (pronounced *leeds*), serve to connect the coil to the commutator. It will be seen that the part *a a* lies in a different plane than the part *b b*, the turn at *c* serving to connect the two. The part *a a* therefore lies in the bottom half of some slot and the part *b b* in the top half of some other slot. The coils lie in two layers and constitute what is sometimes called a **two-layer winding.** This is done in order to keep the end connections from interfering, for all the end connections *e*, from the left-hand side of each coil, extending toward the right, are beneath the end connections, from the right-hand side *d*, extending toward the left. This will be more readily understood from Figs. 22 and 23, which show a few coils of each type on the armature core. In Fig. 23 the right-hand sides of the two coils have not been forced down into position in the slot.

FIG. 21

In Fig. 22, it will be seen that the end connections beyond the slots are supported by flanges that give the completed armature a cylindrical appearance, from

which it is called a **barrel-wound,** or **cylindrical-wound,** armature. In Fig. 23, the ends of the coils bend down over the end plates of the core instead of projecting straight out. In Fig. 24 is shown an end view of a complete armature wound with coils similar to Fig. 21; this type of winding is appropriately called a **spiral,** or **involute,** winding. The various turns making up the individual armature coils are held in place by tape.

Fig. 24

30. Ring-wound coils are almost invariably made like Fig. 12, except that the face conductors are usually wound in slots in the armature core. Sometimes ring-wound coils

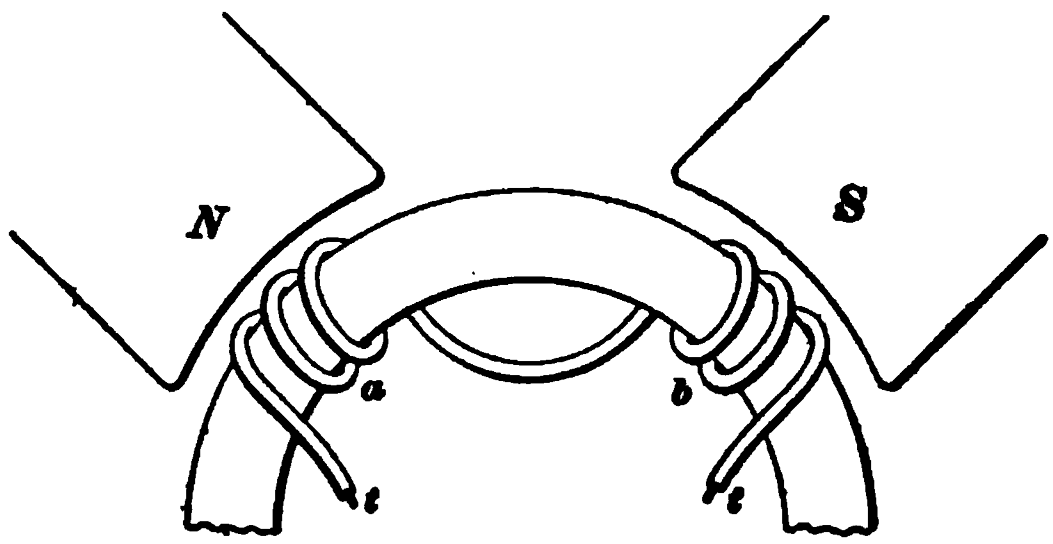


FIG. 25

are connected two in series, as shown in Fig. 25. By the definition of a coil previously given, this would be but a single coil, although composed in reality of two coils *a* and *b* connected in series.

The only advantage this type of coil has over the plain ring-wound coil is that less commutator segments are required than if the same number of parts of coils were connected up as plain ring coils. This is obviously so, since there are only half the number of coils that there are parts of coils. This winding is, in action, exactly the same as a drum winding, for it has face conductors under each of two adjacent poles and what was stated about the proper spread of drum-wound coils also applies to this winding. Notice that the direction of winding the two parts is different so that the E. M. F. developed under opposite poles will be additive in the coil. The winding of Fig. 10 is of this character.

The chief advantage of the drum type of coil is that it can be wound on a form, insulated, and then assembled on the core, while the ring type must be wound in place and cannot be so perfectly insulated at the same expense.

METHODS OF CONNECTING UP COILS TO THE COMMUTATOR

PARALLEL WINDINGS

31. Single Parallel Winding.—The simplest of the methods of connecting up the coils to the commutator is that shown in Figs. 12 and 13, in which the ends of each coil are connected to adjacent commutator segments. This winding is called a **parallel** or a **multicircuit** winding.

32. In Fig. 26 is shown such a winding arranged for six poles. The coils themselves are not shown but only

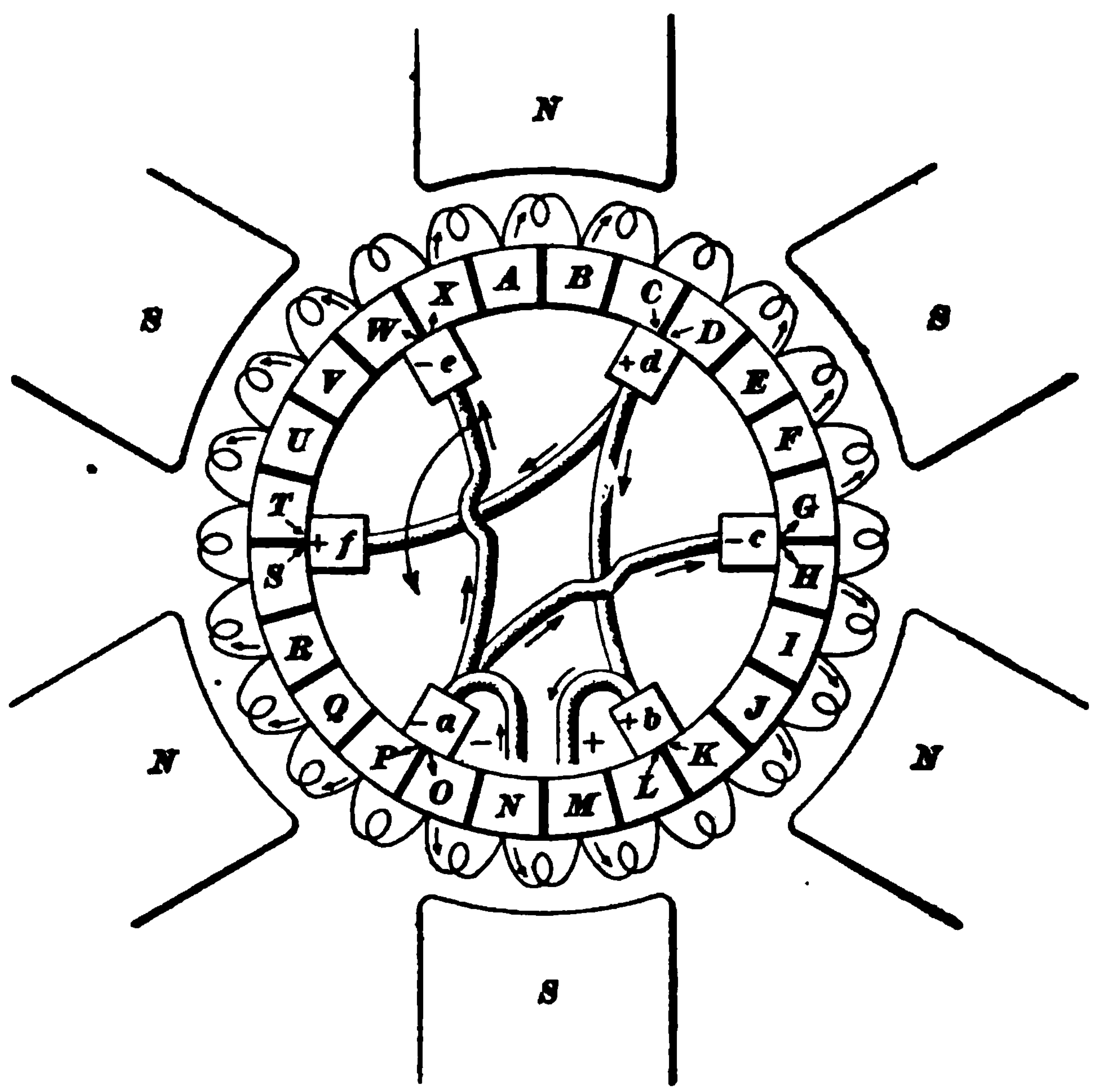


FIG. 26

indicated by the loops from segment to segment. It is immaterial whether these coils are of the drum or ring type so long as they conform to the requirements already explained for armature coils. In Fig. 26 the brushes are shown

rubbing on the inside of the commutator, in order to avoid confusing the diagram.

Note that to each segment there are connected two leads from two different coils. It might be said that to each segment were connected the end of one coil and the beginning of the next, or the right-hand end of one coil and the left-hand end of the next. Now there are but two ends to each coil, and since two ends, or leads, are connected to each commutator segment, it follows that there are just as many segments as coils. This is true for all closed-coil windings of whatever kind.

33. Position of Brushes.—Suppose that in Fig. 26 the brush *a* receives 100 amperes from the negative terminal. The current will enter both segments *P* and *O*, dividing equally, if the winding is symmetrical, so that 50 amperes will flow through the coils *O N–N M–M L*, etc., and 50 amperes will flow through the coils *P Q–Q R–R S*, etc. As the armature rotates, the coil *P O* will pass to the right and 50 amperes current will then flow in it in the direction *P O*. A moment before the position in the figure was reached, the coil was to the left and had 50 amperes in it flowing in the direction *O P*. Thus a current of 50 amperes is reversed in every coil as the segments to which it connects pass the brush *a*, and further it is because the brush delivers 100 amperes to the windings that the current of 50 amperes is reversed. This is evidently true, for if both sets of coils to the right and to the left are to have currents in them flowing away from *a*, the brush *a* must supply the sum of these currents.

34. The E. M. F. generated by a coil reverses when that coil passes from under one pole to one of opposite polarity and the current in the coil should reverse at the same time; hence, in all closed-coil windings, the brushes should be so placed as to come into connection with the coils as they pass through the neutral regions between the poles.

The coil *P O* is about to pass under a south pole and will soon reach the position of *L K*, in the figure, after leaving

which it will pass under a north pole; but before doing this it must again have its current of 50 amperes reversed. From the arrows in the diagrams it is seen that when the position $L K$ is reached, the segments must come in contact with another brush b and deliver thereto 100 amperes. In general it may be stated that in any closed-coil winding, in order that the current in the coils shall be reversed as the coils pass through every neutral region between poles, the segments in which they terminate must come in electrical contact with a brush and current must either be taken from or delivered to the winding by the brush.

35. The neutral points are of two kinds $N S$ or $S N$, and since these must alternate the signs of the brushes also alternate. In Fig. 26, it will be noticed that brushes a, c, and e are negative and brushes b, d, and f are positive. Brushes of the same sign are at the same potential and are shown connected together. They are at the same potential because the poles of the field magnet are alike in size and strength and there are as many coils from a to b as from b to c, each developing the same E. M. F., hence the total E. M. F. developed by the coils a, b is equal to that of the coils b, c in value but of opposite sign, since they are under dissimilar poles, so a and c are at the same potential. In the same way c and e are at the same potential so that the negative brushes are all at the same potential. In the same way it may be seen that the positive brushes also are all at the same potential.

36. In the winding shown in Fig. 26, the current enters by the brushes a, c, and e, dividing at each brush, as shown by the arrows, and going by six paths, or circuits, from the negative to the positive brushes. If any one brush were omitted, two of the paths would not be supplied with current and the remaining ones would have to take more than their share. This would cause an undesirable unbalancing, and parallel or multicircuit windings are therefore always provided with as many brushes as there are neutral points; since there are as many neutral points as poles, there are

as many brushes as poles. Further, it will be seen that such a winding as shown has as many paths as there are brushes, or, it may be stated, has as many paths as there are poles.

37. This type of winding has many paths and is much used for small, low-potential machines with comparatively large current outputs, as well as for all large dynamos of great current output. The numerous paths offer low resistance to the currents, making the heat developed in the windings due to their resistance small, and also keeping down the size of the conductor required on the armature.

Another point to be noticed is that any number of coils whatsoever may be made up into this kind of winding. That this is so may be seen by considering a coil added or omitted in Fig. 26. If the new number of coils are respaced equally, the winding will still have all the properties referred to above.

38. Reentrancy.—In Fig. 26, were we to start at any point in the winding, say at *A*, and follow it around to *B*, to *C*, and so on, we would eventually return to *A*; or, in other words, the winding closes or comes back on itself. It is from this property that the winding is called a closed-coil winding. Another way of expressing the same idea is to say that it is a **reentrant winding.** If we enter the winding at *A* and follow it around until we come again to *A*, the winding is said to reenter. If in following the winding around we traverse all the armature coils before reentering, the winding is said to be **singly reentrant.**

In following the winding, Fig. 26, around from *A* to *B*, *B* to *C*, etc., it will be noticed that all coils are traversed in succession without skipping any, and the commutator is encircled but once. Because of this, the winding is called a **single winding.** It should be evident that single windings are necessarily singly reentrant.

39. Summary.—The full name of a winding in which coils terminate in adjacent segments, as shown in Fig. 26, is **single parallel winding,** also often called a single multicircuit winding. It is singly reentrant, may be formed of

any number of coils whatsoever, have as many paths or circuits from — brushes to + brushes as there are poles, and must be provided with as many brushes as there are poles.

40. Double Winding.—Suppose that between every two commutator segments of Fig. 26, other segments are inserted and another similar winding connected to these segments.

FIG. 27

Fig. 27 shows such a winding; it will be noticed that each coil ends in segments separated by an intervening segment.

The current entering the winding from, say, negative brush *a*, will divide between the segments *O* and *15*. From *O* it goes through the coil *O N–N M–L K*, which is in contact with positive brush *b*. Again, from *a* to segment *15* it goes through coil *15 14–14 13 13 12–12 11*, which again is in contact with positive brush *b*.

41. It will thus be seen that there are now two paths between brushes *a* and *b*, while in Fig. 26 there was but one; and also two paths between *a* and *f*, *c* and *b*, *c* and *d*, *e* and *d*, and *e* and *f*, twelve in all, so this winding has twice as many paths as poles. The brushes used with this winding must be thick enough to always connect to two segments, for if brush *a*, say, only connected to bar *O*, the two paths from *15* would be open-circuited and would not be supplied with current.

42. Investigating the reentrancy of the winding as before, starting, say, at segment *A*, and following it around to *B–C*, etc. to *W–X*, when *A* is reached the winding closes. Only each alternate one of the segments and coils has been included and we have encircled the commutator once. In order to include all the coils it is necessary to again enter, say, at segment *1*, and follow around to *2–3–4*, etc. to *24* and back to *1*, when this second winding reenters. Such a winding is said to be **doubly reentrant.** The commutator has been encircled twice, so that the winding is therefore said to be a a **double winding**; in fact, it is obviously a double winding, since it consists of two interlaced single windings, each exactly like that shown in Fig. 26.

43. It has been stated that a single parallel winding may be wound with any number of coils whatsoever; hence, each of the windings in Fig. 27 may consist of any number of coils. However, since both windings must have the same number of coils, it follows that doubly reentrant, double parallel windings similar to Fig. 27 may be formed from any even number of coils.

44. Singly Reentrant, Double Winding.—In Fig. 28 is shown a double parallel winding for four poles with an odd number of segments and coils. It is a double winding because all the coils terminate in segments removed from one another by one; hence, in following the winding around it will be necessary to encircle the commutator twice before all the coils are included. Starting at segment *A* and following around to *B–C–D*, etc. to *M–N*, it is found that the

commutator has been encircled but the winding does not close, and, continuing, it goes to *1–2–3–4*, etc. t *12–13–A*, closing only after encircling the commutator twice. It is therefore a **singly reentrant, double, parallel winding.** It will be found to have eight paths from negative to positive brushes or twice as many as there are poles.

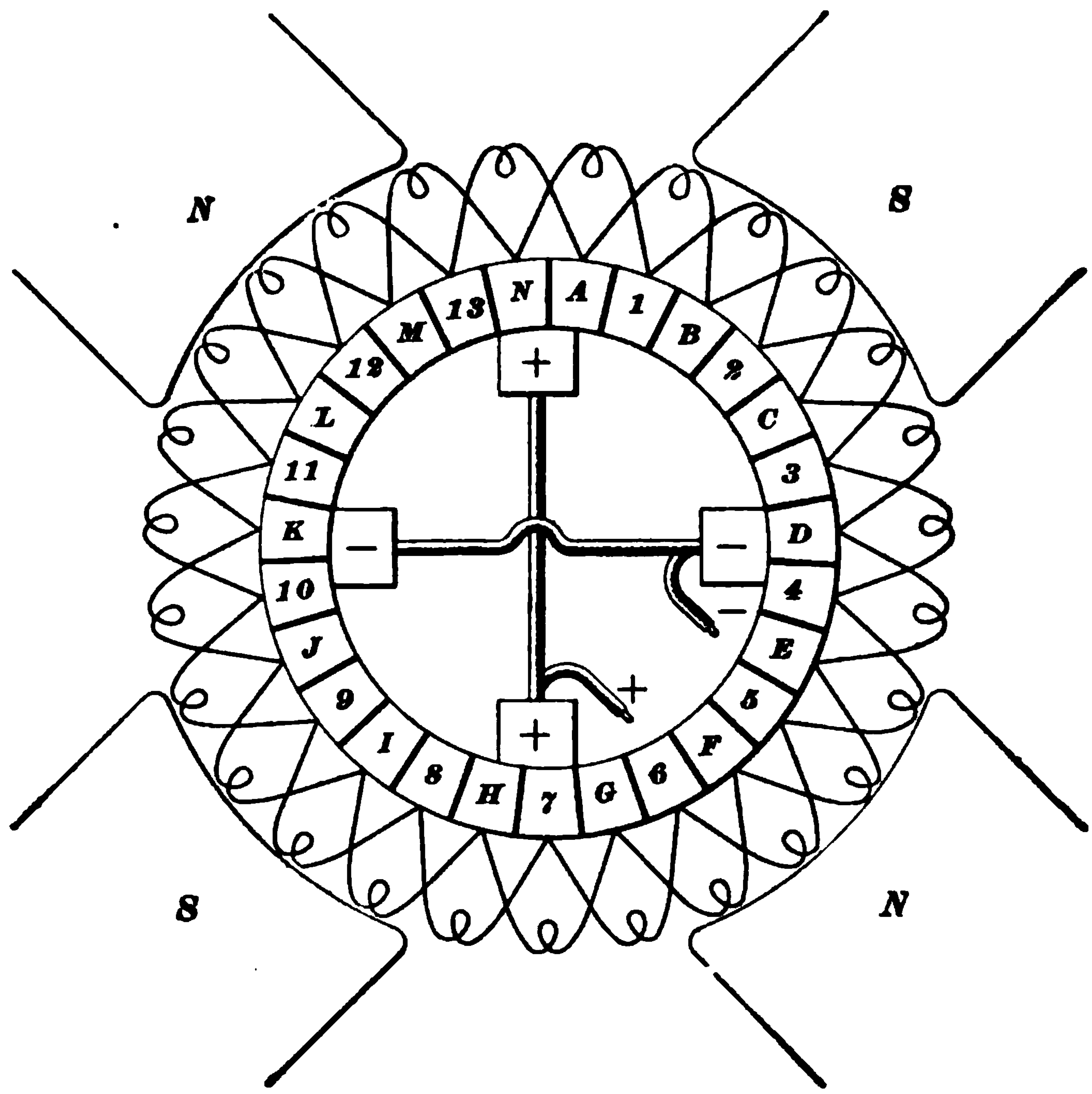


FIG. 28

By omitting two coils in the winding shown in Fig. 28, the resulting winding will be of exactly the same character in every respect so it may be stated generally that to obtain this winding there must be an odd number of segments and coils.

45. Summary.—Double parallel windings are those in which the coils terminate in segments adjacent but one. There must be as many brushes as poles and each must be

thick enough to always touch two segments at once. The winding has twice as many paths as there are poles and any number of coils whatsoever may be connected up into this winding, but if the number of coils is even, the winding will be doubly reentrant, if odd, it will be singly reentrant.

46. Triple Windings.—**Triple windings** are very rarely used, as the action of the commutator is not good on account of the very thick brushes necessary. However, their properties may be determined in the same manner as those for single and double windings and may be stated as follows:

Triple parallel windings are those in which the coils terminate in segments adjacent but two. There must be as many brushes as poles and each must be thick enough to always touch at least three segments at once. There are three times as many paths as there are poles and any number of coils may be connected up into this winding. If the number of coils is divisible by three, the winding will be triply reentrant; if not, it will be singly reentrant.

SERIES-WINDINGS

47. Another type of armature windings is called **series,** or **two-circuit,** in distinction from the parallel, or multicircuit, type already described. It is a peculiarity of the closed-coil windings as distinguished from the open-coil type that there are many coils in series on all paths between brushes. This amounts to the same thing as saying that each coil generates but a small fraction of the voltage of the machine, since this last is only the voltage of a single path, because the paths are connected in parallel, consequently their voltages cannot be additive.

48. Referring to Fig. 26, suppose each coil, except those under commutation, develops 10 volts and also suppose that the negative brushes are at zero potential. Segment P will be at zero potential, being in contact with a negative brush, Q will be at a potential of 10 volts, R at 20 volts, S at 30 volts, which would be the potential of the machine as it

is in contact with positive brush *f*, so *T* also will be at 30 volts, *U* at 20, etc. These potentials are marked on Fig. 29, which shows the commutator of the winding, Fig. 26. It is necessary that the E. M. F. between adjacent segments be kept low; windings in which the potential does not vary approximately uniformly from segment to segment, as shown in Fig. 29, are therefore undesirable. It will be noticed

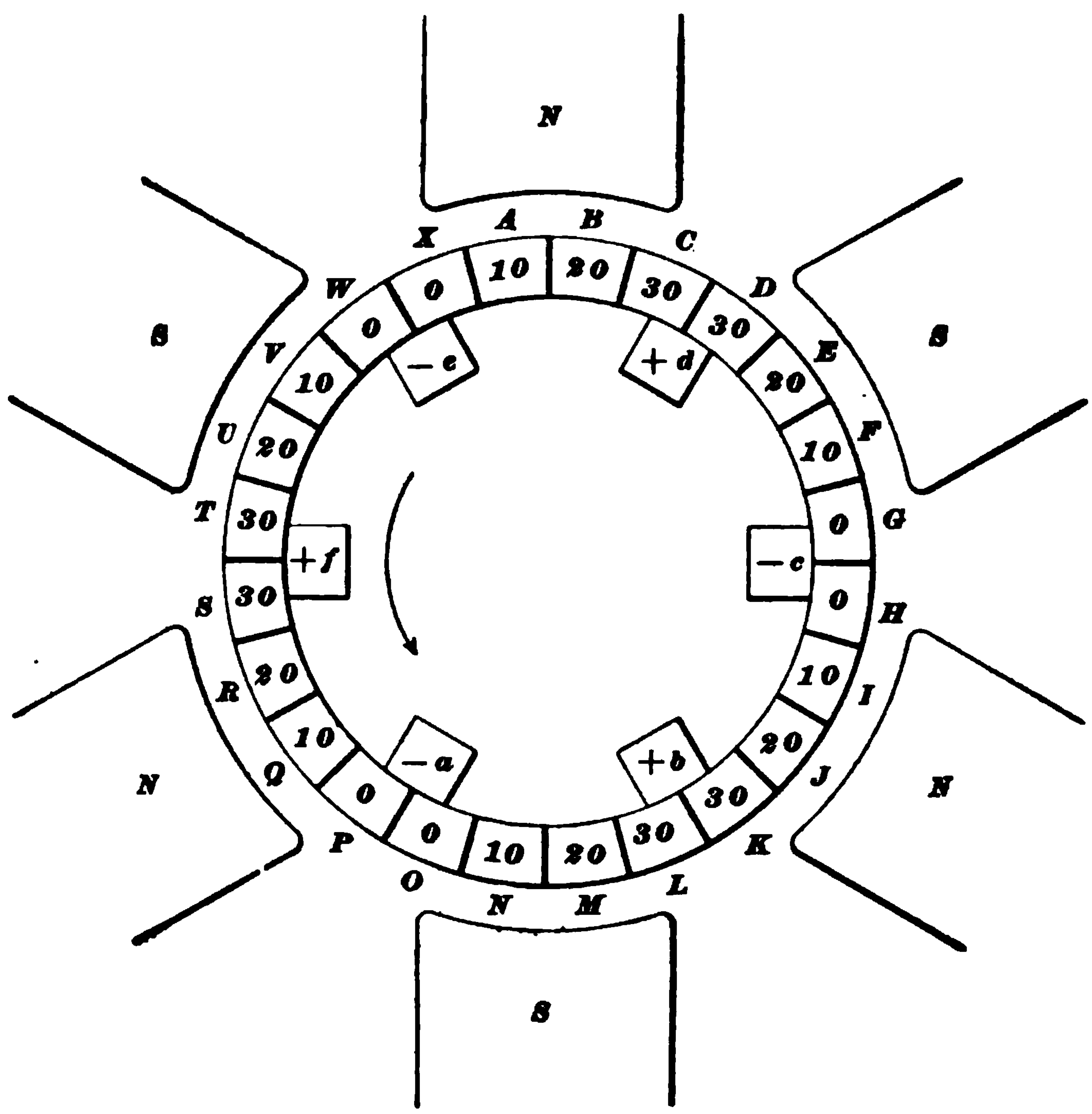


FIG. 29

that the gradations from *a* to *b* are similar to those from *c* to *d* or from *e* to *f*; so that a point between *a* and *b* will always be at about the same potential as a similarly located point between *c* and *d*. Points on the commutator that are about two poles apart will always remain at about the same potential, and, in fact, with parallel windings for large generators it is quite customary to design the windings with a

certain whole number of segments for every two poles and permanently connect all segments exactly two poles apart to large **equalizer,** or **cross-connecting, rings,** which will be illustrated later.

49. In the series-type of winding, the coils are connected to segments removed from one another by approximately the angle of two poles, and, assuming that the potentials on the commutator are to vary about as in Fig. 29, it will be seen that the ends of any coil will not be at any very great potential difference; that is to say, each coil will have to develop but a part of the E. M. F. of the machine. In following such a winding around, an advance of two poles is made for each coil traversed, so that the commutator would be encircled once for every $\frac{p}{2}$ coils, where p is the number of poles. In series-windings, the number of times the commutator is encircled in following the winding out has nothing whatever to do with the number of windings, as it does in the case of the parallel type. In series-windings, the distinguishing feature is the connection of the terminals of this series of $\frac{p}{2}$ coils.

50. Single Series-Winding.—A single series-winding is one in which a series of $\frac{p}{2}$ coils encircles the commutator, and the terminals of this series are connected to adjacent commutator segments. It is immaterial whether this series of coils makes a revolution plus one segment or less one segment on the commutator.

51. In Fig. 30 is shown a diagram of a single series-winding with six poles, so that a series of $\frac{p}{2}$, or three, coils terminates in adjacent segments. It is not intended in the diagram to represent the coils themselves any more than in Figs. 26, 27, and 28, and the lines here shown inside the

commutator are simply to show where the ends of each armature coil are connected. Complete diagrams of these windings will be given later.

52. The winding is much more complicated than a single parallel winding and the diagram must be studied very carefully. Investigating the number of paths in the same

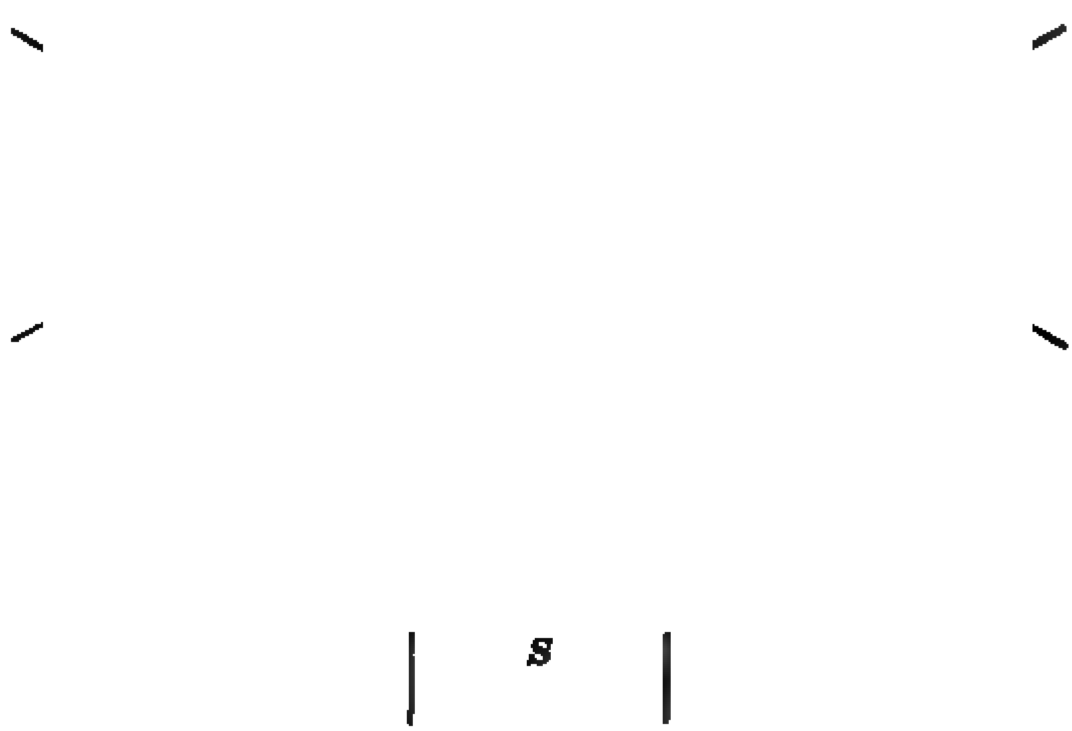


FIG. 30

manner as before, we find negative brush *a* touches segments *29* and *30*. The coil extending from *29* to the right will be found to be connected to segment *8*, from which another coil connects to *19* and to *30*. This, then, is not a path, for both segments *29* and *30* are in contact with brush *a*, which therefore short-circuits the series of coils *29–8*, *8–19*,

19–30 at the instant shown. From *29*, however, another coil connects extending toward the left to *18–7–28–17–6–27–16–5–26–15–4–25–14* to where *3* touches the + brush *b*. This, then, is one of the paths through the winding.

Starting at *a* again and going to segment *30*, another path will be found to connect to *9–20–31–10–21–32–11–22–1–12–23–2–13–24–3* and out. It will be noticed that every coil in the winding has been traversed and that there are but two paths. In fact, the single series-winding has but two paths regardless of the number of poles.

53. It will be noticed that in Fig. 30 but two brushes have been shown in full lines—one positive and one negative—while at the other neutral points they are shown dotted. In following the winding from segment *29* to *8*, *8* to *19*, *19* to *30*, it will be seen that this series of coils has segments *29* and *30* under negative brush *a*, segments *8* and *9* under negative brush *c*, and segment *19* under negative brush *e*. Now it has been stated that the segments to which the coils connect should either be supplied with current or have current taken from them by a brush in order that the current in the coils shall be reversed as the coils pass through the neutral regions, and it is easily seen that the single negative brush *a* is sufficient to accomplish this for the series of coils under consideration without the use of the brushes *c* or *e*. However, the coils *29–8*, *8–19*, *19–30* are, at the instant shown, not developing any E. M. F., being in the neutral region, so the segments to which they connect are practically at the same potential; other brushes *c* and *e* may be put on the commutator and permanently connected to *a* if the brush *a* is not sufficiently large to carry satisfactorily all the current of the armature.

54. Winding Requirements.—If we start at any point in the winding, say at *1*, and follow it around, we find that the coil connects segments *1* and *12*, or it might be said that the ends of the coil span 11 segments on the commutator. The next coil to this is *12–23*, which is 11 coils in advance of coil *1–12*. It would be said of this

winding on this account that the **pitch** was 11. It will be observed that the number of segments spanned by a coil must always be equal to the pitch of the winding numerically. Now since a series of $\frac{p}{2}$ coils encircles the commutator with one segment more or less, and since each coil spans a certain number of segments, called the pitch, it follows that the only numbers of segments that can be used for such a winding will be $\frac{p}{2} Y \pm 1$, where Y is the pitch, being any integer. If C is the number of coils, then C also is the number of segments, so that the number of coils $= C = \frac{p}{2} Y \pm 1$. In Fig. 30, $C = 32 = \frac{6}{2} \times 11 - 1$. Where the minus sign is used it means that a series of $\frac{p}{2}$ coils spans one more segment than a revolution, while the plus sign indicates that $\frac{p}{2}$ coils lack one segment of spanning a complete revolution.

If the winding is followed through from, say, segment *1* to *12*, *23*, *2*, etc., it will be found that before returning to the starting point all the coils and segments will have been traversed; it is therefore a singly reentrant winding.

55. Summary.—A single series-winding is one in which the ends of each coil embrace an angle on the commutator about equal to twice the angle between the centers of poles and in which a series of $\frac{p}{2}$ coils is connected to adjacent commutator segments. It has but two paths or circuits, regardless of the number of poles, and two brushes, one negative and one positive, are all that is required, although all the neutral points on the commutator may be used for brushes if desired. It is singly reentrant, and the number of coils possible for this winding must conform to the following formula

$$C = \frac{p}{2} Y \pm 1, \qquad \textbf{(1)}$$

where $C =$ number of coils;
$p =$ number of poles;
$Y =$ any integer, being the pitch of the winding.

56. Double Series-Windings.—In the same way as with parallel windings, we may double the number of segments and coils of Fig. 30 and connect them up into two separate windings, each exactly like Fig. 30. Such a winding would be a double winding and would be doubly reentrant, since it consists of two separate single windings. Each winding would have two paths, so that there would be four paths for the two windings. However, in order that all the paths may be available, it will be necessary to have brushes thick enough so that at least one of each polarity shall always be in contact with some point in each winding. In regard to the number of coils, it will be noticed that a series of coils end on segments adjacent but one, because between every two adjacent segments we have put in a new segment belonging to the second winding. The new winding would thus have 64 coils and the number of segments would have to conform to the formula

$$C = \frac{p}{2} Y \pm 2 \qquad \textbf{(2)}$$

The value of Y is here 22, as it is double the value in the winding, Fig. 30, and hence,

$$C = \tfrac{6}{2} \times 22 - 2 = 64$$

57. Summary.—In general, double series-windings are those in which a series of $\frac{p}{2}$ coils terminates in segments adjacent but one. The winding will be doubly reentrant if half of the segments and coils can be connected into a single series-winding. Dividing formula **2** by 2 gives

$$\frac{C}{2} = \frac{p}{2} \times \frac{Y}{2} \pm 1$$

Comparing this with formula **1** for C, for the single series-winding, it will be seen that this value of $\frac{C}{2}$ will form

a single series-winding if $\frac{Y}{2}$ is an integer, or, in other words, if Y is an even number; if Y is odd, the winding will be singly reentrant.

From what has been shown, it can be said that a **triple series-winding** is one in which the series of $\frac{p}{2}$ coils terminate in segments adjacent but two. The number of coils possible must satisfy the formula

$$C = \frac{p}{2} Y \pm 3 \qquad (3)$$

The winding will have six paths regardless of the number of poles, and while two brushes are all that is necessary, they must be thick enough to touch at least one segment of each winding at all times. The winding will be triply reentrant if Y is divisible by 3 without a remainder, if not, it is singly reentrant.

58. Single windings are very generally used, double windings, both parallel and series, are occasionally found, while triple and quadruple are seldom if ever used in practice today. It often happens that a number of different windings are possible with a certain number of segments and bars (which is a great advantage, as will be explained later, for the same armature winding, so far as coils and commutators are concerned, may be used for several voltages). By using different commutator connections, the different windings may be made to give different voltages. For instance, the winding, Fig. 29, for six poles thirty-two coils and bars may be connected into a single or double parallel winding, since any number of coils may be used for these windings. It can also be connected as a single series-winding, and since $32 = C = \frac{6}{2} \times 10 + 2$ it can also be used for a double series-winding. All six-pole windings have this advantage.

Singly and doubly reentrant windings do not differ at all in operation and there is no special advantage with either;

TABLE I

	Parallel Windings*			Series-Windings†		
	Single	Double	Triple	Single	Double	Triple
Coils terminate in	Adjacent segments	Adjacent but one segment	Adjacent but two segments			
A series of $\frac{p}{2}$ coils terminate in				Adjacent segments	Adjacent but one segment	Adjacent but two segments
Number of paths	As many as poles	Twice as many as poles	Thrice as many as poles	Two	Four	Six
Brushes must always touch at least	One segment	Two segments	Three segments	At least one brush of each sign must always touch a segment of each winding		
Number of times reentrant	Singly	Singly if odd Doubly if even	Singly if not divisible by three Triply if divisible by three	Singly	Singly if Y is odd Doubly if Y is even	Singly if Y is not divisible by three Triply if Y is divisible by three
Number of coils possible in winding	Any	Any	Any	Coils $= \frac{p}{2} Y \pm 1$	$C = \frac{p}{2} Y \pm 2$	$C = \frac{p}{2} Y \pm 3$

* Require as many brushes as poles.

† Require but two brushes.

the reentrancy of a winding is simply a matter of interest to the student.

59. It will be noticed with regard to the restrictions as to the numbers of coils in the single series-windings that if $\frac{p}{2}$ is even C must be odd or else the winding is impossible, but if $\frac{p}{2}$ is odd then C may be either odd or even according as Y is even or odd. For four poles or eight poles, any odd number will do, while for six poles any number of coils not divisible by three is possible. For eight, ten, or more poles series-windings are rarely used and thumb rules are a burden rather than a help.

60. The important peculiarities of the various windings that have been considered are collected for comparison and reference in Table I.

THE MAGNETIC CIRCUIT

61. As far as the generation of the E. M. F. of the dynamo is concerned, it is only essential that the lines of force of the magnetic field be present at the points where they are cut by the conductors, and have the proper direction and distribution. However, since each line of force is continuous, forming a closed circuit, provision must be made for a complete path for the lines of force to and from the points where they are cut by the conductors, and through the magnetizing coil or coils wherein they are generated. Of course, they might be left to find their own circuit through the surrounding air, but in order to obtain the large number of lines of force required with the expenditure of a reasonable amount of magnetizing force, it is necessary that the path of the lines of force be of as great a permeability as possible; i. e., through an iron or steel **magnetic circuit.**

In addition to the armature and its winding, a bipolar or multipolar dynamo must have an iron or steel frame, or

field magnet, which completes the magnetic circuit outside the armature. This frame is made up of one or more pairs of pole pieces, from (or into) which the lines of force pass to (or from) the armature through the spaces between the faces of the pole pieces and the surface of the armature core, which are called the air gaps; it must also have a part upon which the magnetizing coils are wound, which part is called the **field core.** The part of the frame that joins together the field cores, if more than one is used, or that joins the pole pieces and the field cores, is called the **magnetic yoke.**

62. It will be seen that the object of the frame, as a whole, is to so guide the lines of force that are set up by the current in the magnetizing coils that they will enter and leave the armature at the proper points, forming the magnetic field in the air gaps of the required distribution and density.

It is not essential to the operation of the machine that the frame be of any given form or size, so long as the lines of force are properly delivered to the armature; economy in materials or labor, mechanical strength, and other considerations determine the form and size of frame to be adopted.

63. Since the magnetic circuit may be considered analogous to an electric circuit, it will be seen that in order to obtain a large number of lines of force with a moderate magnetizing force, the reluctance of the circuit must be low; that is, the iron should be of considerable cross-section and the circuit of moderate length. It should be remembered that, since the permeability of the best of iron is only, perhaps, 1,500 times that of air, a considerable number of lines of force that pass through the magnetizing coil complete their circuit around through the air without passing through the air gaps. To reduce this magnetic leakage as far as possible, surfaces between which there is a great difference of magnetic potential should be kept as far apart as the design of the magnet will allow, and made of as small area as possible. In any case, some leakage is bound to

occur, and this must be provided for by making those parts of the frame through which the leakage lines pass of sufficient area for both the useful and the leakage lines. The conditions that govern the leakage will be more fully discussed later; in general, the area of the iron in the frame must be sufficient for from 10 to 50 per cent. more lines of force than are used in the armature.

DENSITY OF LINES OF FORCE

64. Referring to the saturation curves for iron and steel, *The Magnetic Circuit*, it will be seen that the saturation curves there shown rise in a nearly straight line for some distance from the origin, then curve away from the axis of the ordinates and follow another approximately straight line, which makes a much greater angle with the axis of the ordinates than does the first-mentioned line. This effect is much more marked in the case of wrought iron and cast steel than with cast iron, but in any case it will be seen from this feature of the saturation curves that the most economical density at which to work the iron of the magnetic circuit is that in the vicinity of the bend, or "knee," of the curve. A much lower density could not be economically used, because a considerable increase in the number of lines of force could be obtained with comparatively little increase in the magnetizing force required; and on this account accidental small changes in the magnetizing force would produce a considerable change in the number of lines of force, so that the magnetic circuit of the machine would be in an unstable condition. A much higher density would not be economical, because the increase in the number of lines of force could be obtained only by a very considerable increase in the magnetizing force.

65. Applying these statements to the curves just mentioned, it will be seen that, in general, cast-steel and wrought-iron forgings should be worked at densities of between 80,000 and 100,000 lines of force per square inch, while sheet iron

may be worked higher—between 90,000 and 110,000 lines of force per square inch. With cast iron, the curves being flatter, the allowable range is somewhat greater, the usual range in practice being from 25,000 to 50,000 lines of force per square inch, the latter value being used only in the case of the best grades of soft, gray cast iron.

The best densities to use are, therefore, not those that give the maximum permeability of the iron used, as at that point the iron would be in the unstable condition referred to previously.

66. From the foregoing, and from the curves referred to, it appears that for the same expenditure of magnetizing force a cast-iron magnetic circuit must have about twice the sectional area of one of cast steel or wrought iron, in order to obtain the same number of lines of force, so that the cast-iron magnetic circuit will be about twice as heavy as one of steel or wrought iron. As it costs considerably less per pound, however, this extra weight is often counterbalanced; in fact, the choice of materials for the frame, as well as almost all the other features of a dynamo, depends on the special conditions governing each particular case.

67. The density used in the air gaps varies, but the best practice fixes it somewhere between 30,000 and 70,000 lines of force per square inch, depending on the design. In any case, the amount of the magnetizing force that is required to force the magnetic flux through the air gaps is a large proportion of the total amount, since the permeability of the air gaps is 1, which much more than compensates for their comparatively short lengths.

FORM OF MAGNETIC CIRCUIT

68. The form of the magnetic circuit is subject to many variations; there are, however, two general classes into which they may all be divided. In the first, a single source of magnetizing force for each pair of poles (which may reside in one or more magnetizing coils) sends the lines of

force around through a magnetic circuit, of which the air gaps and armature directly form a part. Such an arrangement is said to have **salient poles.** In the second type, at least two magnetizing forces are necessary for each pair of poles; these magnetizing forces act in opposite directions upon a complete magnetic circuit, and the opposing lines of force cause poles to appear at points on the magnetic circuit, which points are properly provided with pole pieces, between which the armature is located. Such an arrangement is said to have **consequent poles.**

69. One of the simplest forms of salient-pole bipolar field magnets is represented in Fig. 31. In this form the magnetizing force is supplied by the single coil shown in section at *W*, *W*. This surrounds the field core *C*, to which are attached the magnet yokes *M*, *M*, which terminate in the pole pieces *N*, *S*, between which the armature *A* revolves. The mean paths of the lines of force through the magnetic circuit (neglecting leakage lines) are indicated by the dotted lines having the arrowheads, which indicate the direction of the lines of force, assuming the polarities of the pole pieces to be as indicated by the letters *N*, *S*. In this figure the field core is represented as being vertical; this type of magnet is so used in certain machines of English make. It may, however, be either vertical or horizontal, and be above, below, or on either side of the armature, as desired. The Jenney motors, the Wood bipolar machines, the Holtzer-Cabot small motors, and others made in this country have used this type of magnets with the coil horizontal and below the armature. Further, the armature shaft may either have the direction indicated or be at right angles to that direction, if desired, without changing the character of the field magnet. The mechanical construction in this last case would evidently be bad, and this

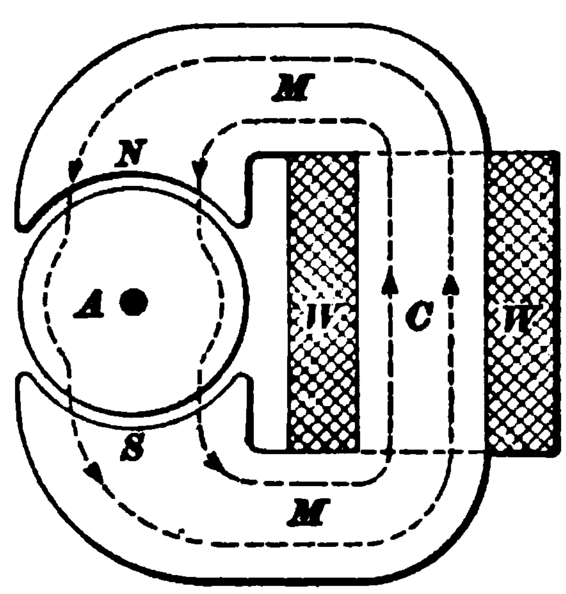


FIG. 31

is generally the principal feature that determines the disposition of the magnet frame with regard to the armature.

70. A form of consequent-pole field magnet derived from that just described is shown in Fig. 32. This form is known as the *Manchester type*, and has been used by the Mather Electric Company, the Westinghouse Company, and others in this country. It is practically the same form of magnet as that shown in Fig. 30, with the addition of a second similar magnet situated on the opposite side of the armature A, as indicated by the letters N', M', C', M', and S'.

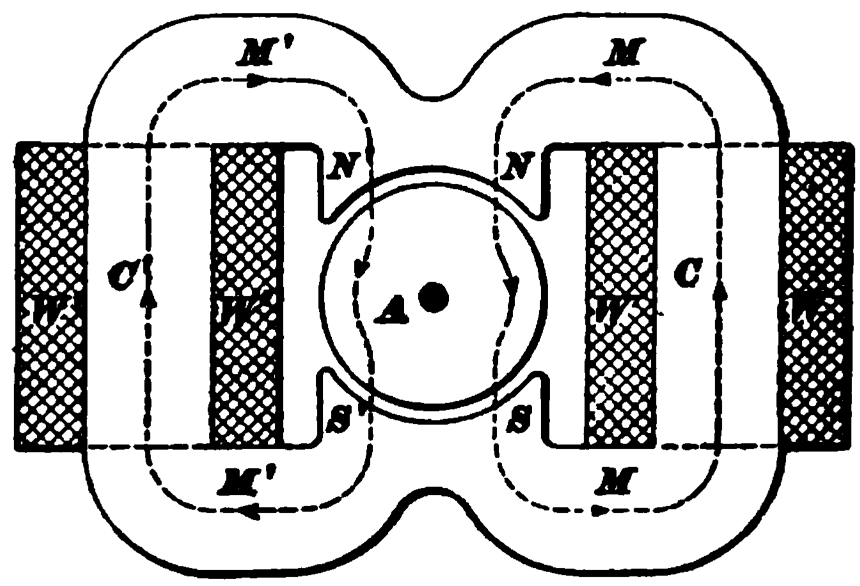


FIG. 32

Assuming that the same total number of lines of force passes through the armature in each case, it follows that with the consequent-pole magnet, Fig. 32, each half of the magnetic circuit contains half the total number of lines, and needs, therefore, to be of but half the sectional area of the frame of the salient-pole magnet, which carries all the lines of force, as is indicated by the relative proportions of the two magnets. (See Figs. 31 and 32.) Consequently, the weight of the frame in either case is about the same.

71. In the consequent-pole magnet, the magnetic circuit in each half is approximately the same length but of half the area as that of the salient-pole magnet; its reluctance is about twice as great, but since it carries half the number of lines of force, it follows that the magnetizing force required for each half of the consequent-pole magnetic circuit is the same as that required for the whole of the salient-pole magnet. However, the magnetizing coils on the consequent-pole magnet are of smaller diameter than those used in the salient-pole magnet, so that the weight of copper used for the magnetizing coils of the former type of magnet is not

double that required for the latter type. The actual ratios of weights of copper and iron may be readily calculated for any particular case, but there are other conditions that influence the choice of the form of magnet to be used, which must be taken into account.

72. Fig. 33 shows the adaptation of these two forms of field magnets to a multipolar machine. In the figure, the part to the left of the vertical diameter represents the salient-pole magnet, and that to the right represents the consequent-pole magnet, each being laid out as for an eight-pole magnet.

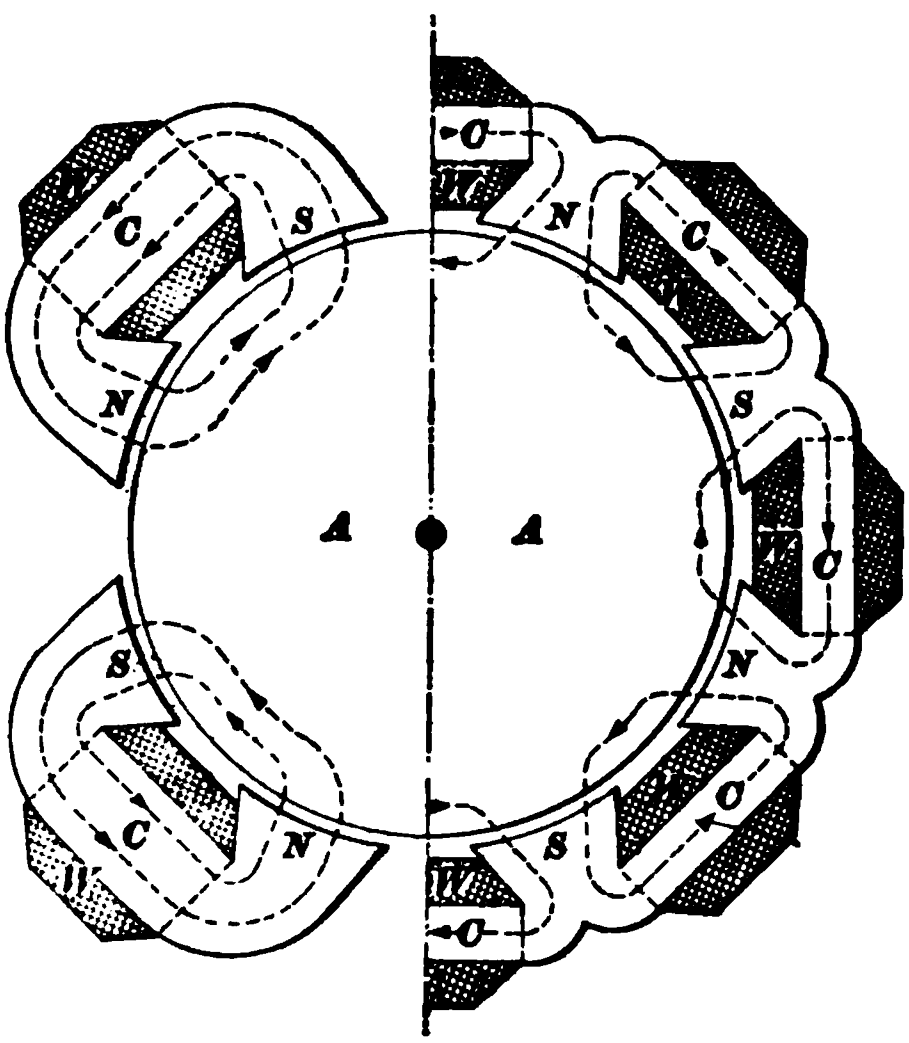


FIG. 33

The salient-pole magnet consists of a number of separate magnets, each with its magnetizing coil. It is, therefore, necessary to supply some separate support for these magnets. In the consequent-pole magnet, however, the whole frame is continuous, each pole piece being supported by a field core on each side, the frame, therefore, being of sufficient mechanical strength for its own support. In the latter form, the mean length of the magnetic circuit for each pair of poles is less than with the salient-pole magnets, which results in a slight saving in magnetizing force, other things being equal.

Of the above types of magnets for multipolar machines, the salient-pole type has been used in the Perrett machines, built by the Elektron Manufacturing Company, and the consequent-pole type has been used by the Standard Electric

Company, in this country, and in several types of machines made abroad.

73. The two simple forms of field magnets that have been described may be considerably modified by changing the position or increasing the number of the field coils. For example, the magnetizing coil of the salient-pole magnet, Fig. 34, may be wound over the entire frame from pole piece to pole piece, as in the old style ring-type machine of the Mather Electric Company. Similarly, the magnetizing coil on each half of the consequent-pole magnet, Fig. 35, may be wound over the entire frame from pole piece to pole piece, as in the C & C machines. In both these examples, the field cores are made approximately circular in outline.

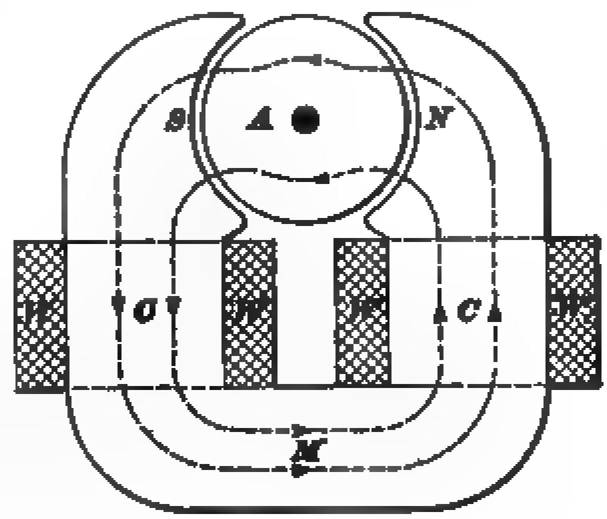


Fig. 34

Further, by dividing the magnetizing force between two coils, and locating these coils in the part indicated as the magnet yoke *M*, *M*, Fig. 31, a type of field magnet results that is commonly known as the **horseshoe** type, as illustrated in Fig. 34. It will be seen that in these two forms the magnet yoke *M* of each corresponds to the field core of the other. This type of field magnet is very extensively used for bipolar machines, the Thomson-Houston, Crocker-Wheeler, Keystone, and other makes of machines using it in the position shown, i. e., with the magnet frame beneath the armature.

Fig. 35

The General Electric Company, in their Edison machines, the Eddy Electric Manufacturing Company, and others have used the same form of magnet in the reverse position, i. e., with the magnet frame above the armature.

The Excelsior arc machine employs the same type of magnet, but with the armature shaft parallel to the field cores, passing, therefore, directly through the magnet yoke. The pole pieces are necessarily modified in shape to suit the changed position of the armature, and are extended to embrace the three outside faces of the armature, which is ring wound.

74. The consequent-pole magnet that results from combining two horseshoe magnets of the types illustrated in Fig. 34 is shown in Fig. 35. Here the various letters have the same reference as in the previous figures. As in that previously described, the consequent-pole arrangement requires only half the cross-section of metal in each half of the magnetic circuit, but the total amount used is about the same. This is also a commonly used type of bipolar field-magnet. Among others, it is used in the Wood arc machine of the larger sizes, in the position represented in the figure, i. e., with the field cores *C*, *C*, *C*, *C* vertical. The Weston machine used the same form of field magnet, but with the field cores horizontal; it has also been used in this same position for various special machines built by the General Electric Company and others.

The smaller sizes of the Wood arc machine use this form of magnet with the field cores horizontal, and with the shape of the pole pieces modified so as to allow the armature shaft to be parallel to the field cores, it passing through and having its bearings in the yokes *M*, *M*. The Brush arc machine uses a similar construction, but the armature is made in the form of a ring-wound disk with the pole

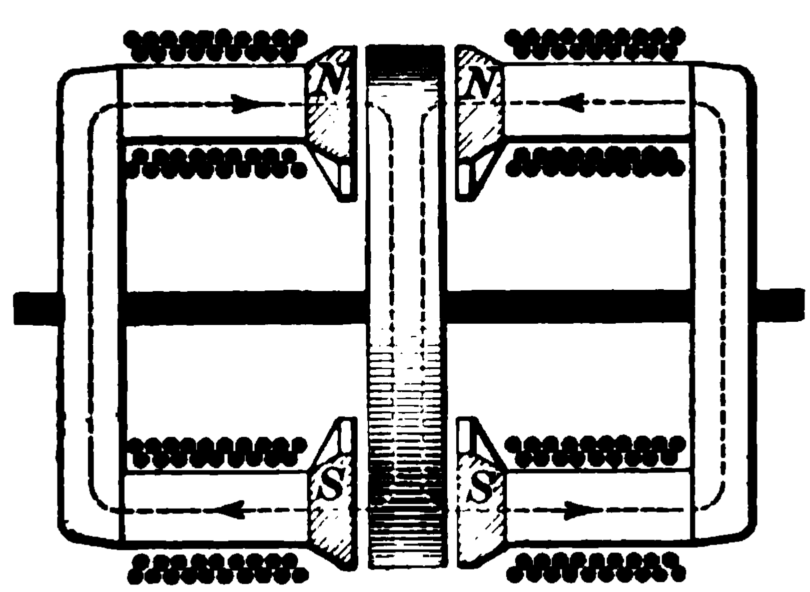


FIG. 36

faces toward the end faces of the armature, as represented in Fig. 36. The magnet in this case might be considered to be two separate bipolar, salient-pole, horseshoe magnets.

75. By carrying the magnetizing coils still farther along the frame, until they are as close as possible to the ends of the pole pieces, still another type of field magnet results, as represented in Fig. 37. As shown, this is a very heavy and

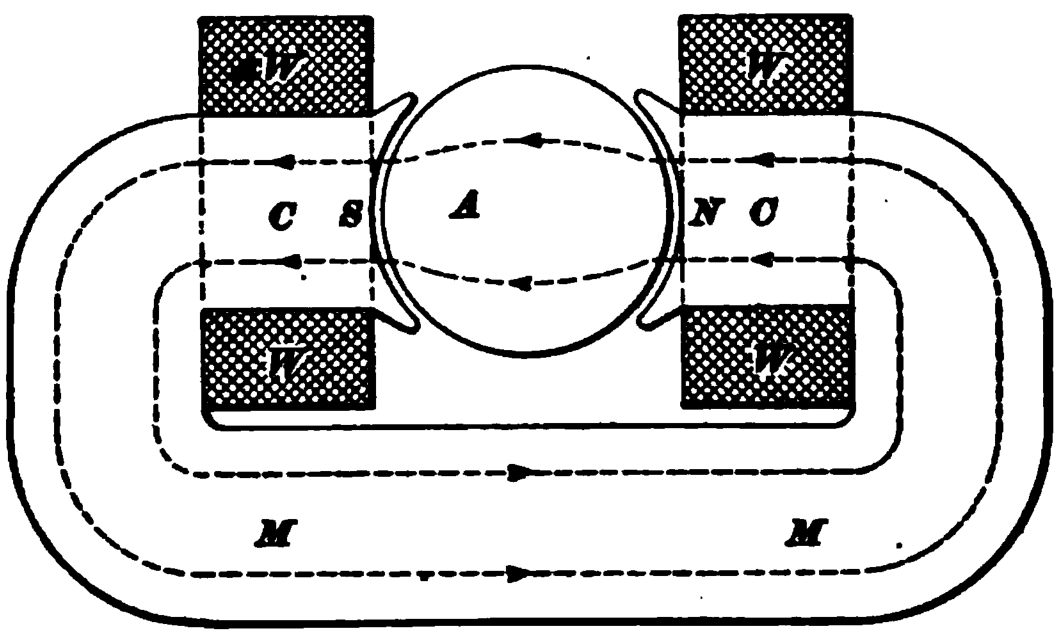


FIG. 37

clumsy magnet, requiring a large amount of material on account of the length of the magnet yoke *M*, *M*. If, however, half the material in this yoke is located on the other side of the armature, so that the magnetic circuit through the frame from field core to field core consists of two branches, a much neater and lighter magnetic circuit, which is quite extensively used, results, as represented in Fig. 38.

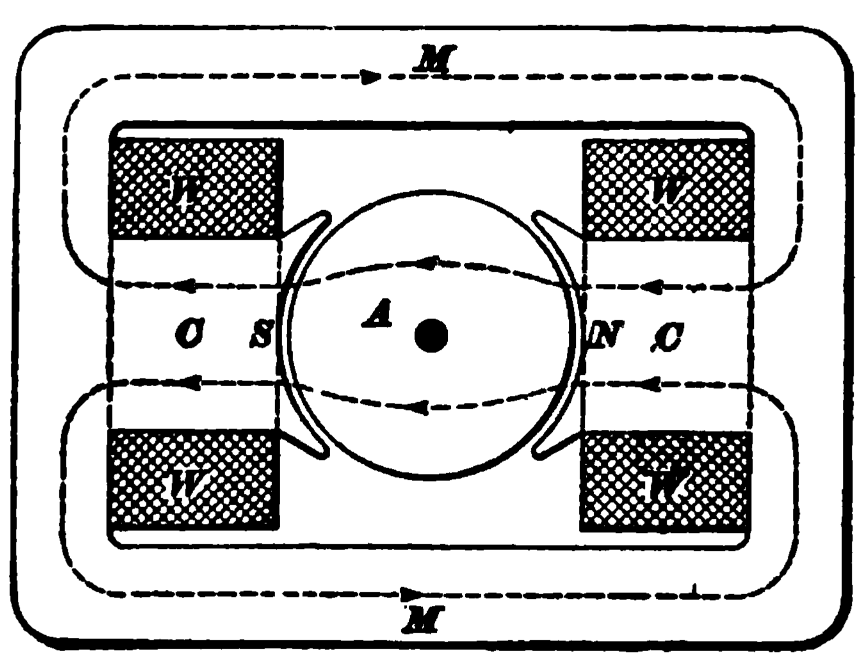


FIG. 38

This form of circuit still has salient poles, since the poles are produced by the direct action of the magnetizing forces and not by the opposition of two magnetizing forces. It has the advantage that the

magnetizing coils and armature are enclosed by the frame, thus affording them mechanical protection.

The Thomson-Houston arc-lighting dynamos employ this type of field magnet, the form being modified by making the magnet yokes of a series of round, wrought-iron bars, which connect together circular flanges on the ends of the field cores, thus making the general outline cylindrical. Eickemeyer used it for very compact machines in which the magnetizing coils actually enclose the armature, the field cores being very short.

The same form of magnet, but with the magnetizing coils above and below the armature, was used in the old Hochhausen dynamos, also by the Thomson-Houston Company for their old "S. R. G." railway motors, and by others.

76. With this arrangement of the magnetizing coils, a consequent-pole bipolar magnet is not possible; but by reversing one of the coils so that the two magnetomotive forces are opposite, two consequent poles will be formed on the magnet yokes *M*, *M*, Fig. 39, at a point opposite the neutral spaces of the bipolar form; and by locating suitable pole pieces at these points, a four-pole magnet results, as represented in Fig. 39. It will be seen that this magnet has one pair of salient poles *N*, *N* and one pair of consequent poles *S*, *S*. This gives a very compact form of four-pole magnet, and is used in several types of railway motors, in the Eddy slow-speed stationary motors, and by other makers. The Wenstrom dynamos also had a modified form of this type of field magnet, the magnet yoke being barrel-shaped and completely enclosing the magnetizing coils and pole pieces, spaces being left in the sides for the removal of the armature.

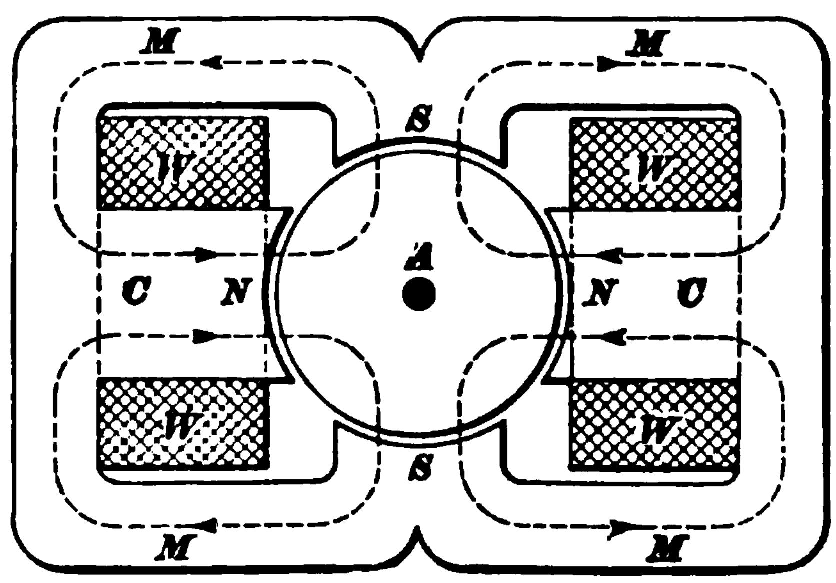


FIG. 39

77. By winding magnetizing coils around the consequent poles of the type of magnet illustrated in Fig. 39, they become salient poles, giving still another type of field magnet, illustrated in Fig. 40. The same letters of reference are used in this figure as in the previous ones. This is a very useful form of field magnet, and is the one most generally used in this country for multipolar machines of any number of poles, almost every maker using it for multipolar generators and alternators.

FIG. 40

The various magnet yokes form a complete ring, which is usually, especially when six or more poles are used, made circular in outline. A modification of this form of magnet has been used by the Siemens & Halske Company, in which the field cores project radially outwards from a common hub instead of inwardly, the armature revolving outside the poles of the magnet.

78. The number of possible forms of field magnets is very great, although they may all be classed as either salient or consequent pole magnets, or combinations of the two. Many of the forms of magnets that have been and are used seem to have been designed merely with a view to getting something different from any other maker, and considerations of economy of material or of mechanical fitness, which should prevail in the selection of a design, have been largely neglected. These forms described are the basis of the designs of field magnets in modern construction. Nearly all modern machines are multipolar except in the small sizes or in the case of machines designed for exceptionally high speed. The type of field magnet that is by far the most commonly used is that shown in Fig. 40. This design gives an economical distribution of material, it can be easily adapted to any number of poles, and it also gives a machine

of graceful outline. In some cases the pole pieces are cast with the yoke while in others they are bolted to the yoke. In most modern machines the pole pieces are laminated and are either bolted to the yoke or cast into it.

METHODS OF EXCITING THE FIELD

79. The requisite number of ampere-turns for exciting the field of a dynamo-electric machine may be obtained in a variety of ways. In the first place, the current that flows through the magnetizing coils may come either from some separate external source, the machine being then said to be **separately excited,** or it may be furnished by the armature of the machine itself, it being then said to be **self-excited.** In some cases a combination of separate and self-excitation may be used.

A diagram illustrating separate excitation is given in Fig. 41. The current required is in this case supplied by

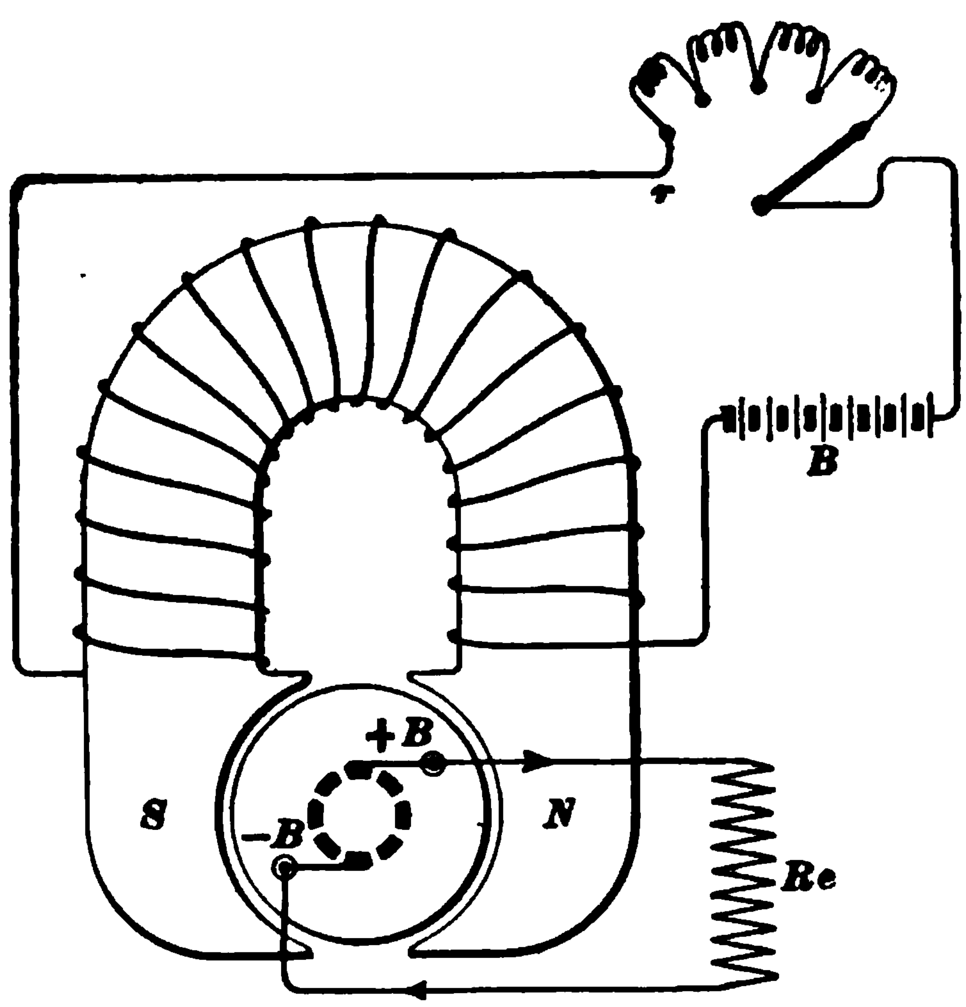


FIG. 41

the primary or secondary battery B, although another dynamo may be used, if desired. In order to adjust the

current in the magnetizing coils to the proper value, or to vary it if necessary, an adjustable resistance *r* is included in the field circuit.

The armature has no connection whatever with the field circuit, but supplies the external circuit *Re* directly.

80. It is evident that with self-excitation a small or a large current may be used in the magnetizing coils, according to the nature of the source of the current, a large or a small number of turns being used in the magnetizing coils to give the necessary magnetizing force.

Alternators are usually separately excited, since the current given out by the machine, being alternating, cannot be used directly for the purpose. Separate excitation has also the advantage that variations of the output of the armature of the machine, caused by changes in the speed or of the current, do not directly affect the field excitation.

81. Characteristic Curves.—In order to study the behavior of dynamos, it is instructive to lay out curves showing the relation between the current delivered by the armature and the E. M. F. at the terminals of the machine, or the E. M. F. generated in the armature. For example, in the case of the dynamo shown in Fig. 41, suppose the field is kept at a constant strength and the armature run at a constant speed. The external resistance *Re* is then varied so that the current supplied by the armature is varied in amount. If an ammeter is connected in circuit and a voltmeter connected across the brushes, we can, by varying *Re*, take a series of readings and obtain the voltage readings corresponding to the various current readings. These points can then be laid off on cross-section paper, as shown in Fig. 42, and a line or curve *a b* obtained; this curve is called the **characteristic curve,** or **characteristic,** of the dynamo. Volts are laid off as ordinates and amperes as abscissas.

With a separately excited machine, it will be found that the voltage falls off as the current increases, as indicated by the drooping of *a b*. This falling off is due to two causes.

In the first place, a portion of the total E. M. F. generated in the armature is used in forcing the current through the armature itself; hence, the voltage at the armature terminals is decreased by an amount equal to the voltage drop in the armature. The volts lost in the armature and at the

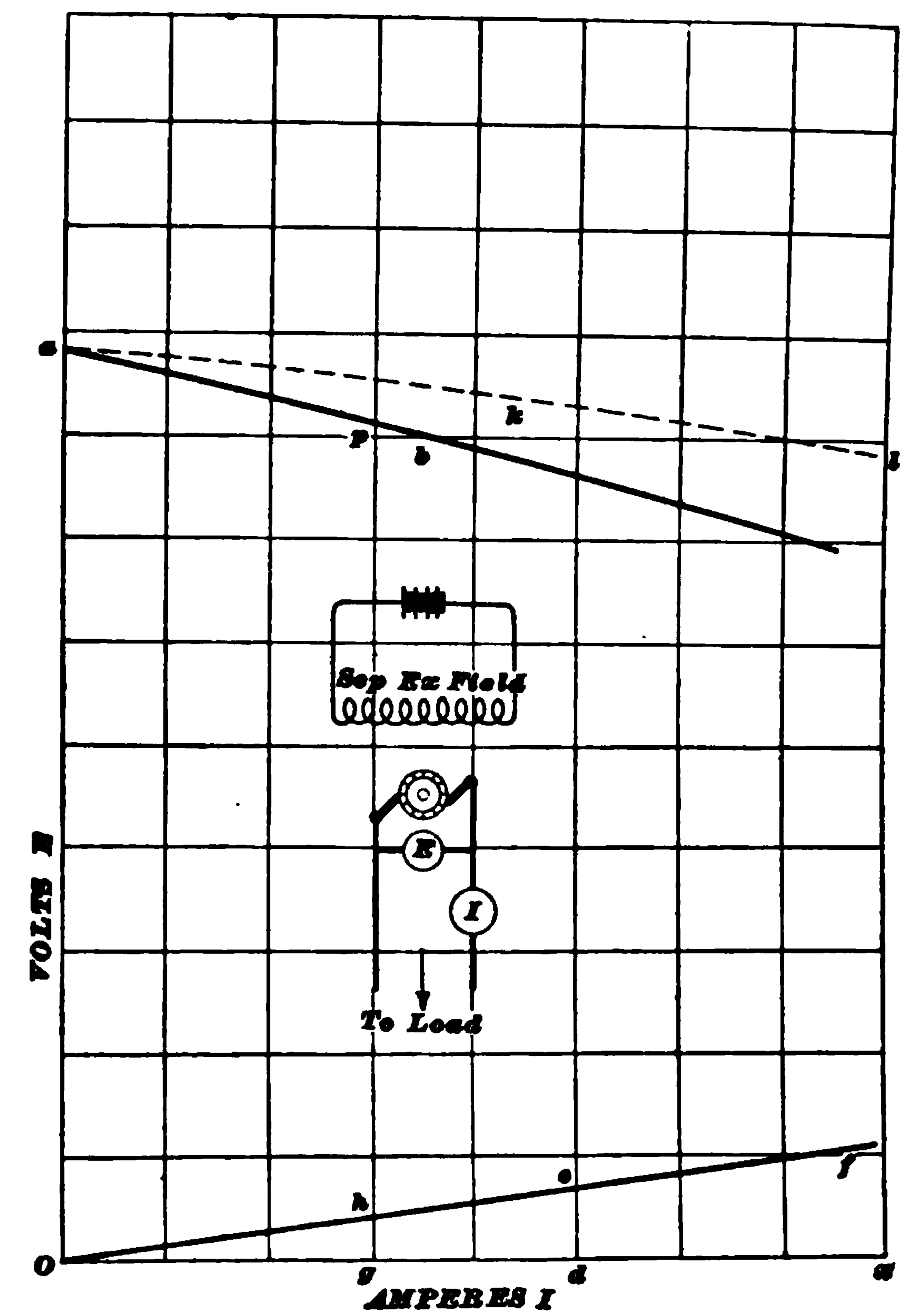


FIG. 42

brush contacts can always be found by multiplying the current by the resistance between the brushes, or if I is any given current and R_a the resistance between brushes, then the volts lost corresponding to the current I will be IR_a. At zero load it is evident that the voltage at the brushes will be equal to the voltage Oa generated in the armature,

because there is then no drop in the armature. Another cause of the falling off in voltage is the weakening of the magnetic field by the current flowing in the armature. This will be fully explained later on in connection with armature reaction. For the present it will be sufficient to state that when current is taken from an armature, the magnetizing action of the armature currents is to a certain extent opposed to the original field and weakens it somewhat. This reduces the total E. M. F. developed in the armature, and this in turn causes a falling off in the E. M. F. at the brushes. If it were not for the demagnetizing action of the armature, the field strength in a separately excited dynamo would remain constant, because the current flowing around the field winding is constant.

82. The line *a b* is often called the **external characteristic** of the separately excited dynamo, because it shows the relation between the load or current and the external voltage. If the relation between the current and the internal voltage, i. e., the voltage actually generated in the armature, is to be represented, the armature drop or loss in voltage must be added to the ordinates of the curve *a b*. This is easily done as follows: Select any value of the current, say the number of amperes corresponding to the distance *O d*, and multiply this current by the resistance of the armature between brushes. Lay off this value of the drop or lost voltage, as shown by *d e*. For example, if *O d* were 50 amperes and the resistance between brushes .05 ohm, then *d e* would correspond to $50 \times .05 = 2.5$ volts. Now the armature drop increases directly as the current, so if we draw a line *O e f* through the points *O* and *e*, the vertical distance between *O x* and this line will represent the drop corresponding to the current. For example, the armature drop corresponding to the current *O g* is *g h*. In order, then, to obtain the curve representing the total E. M. F. generated in the armature, the ordinates of the line *O e f* are added to those of the curve *a b*, thus giving the dotted curve *a k l*. The dotted curve is sometimes called the **total characteristic** of the

machine because it shows the relation between the current and the total E. M. F. developed in the armature.

83. In a separately excited dynamo, therefore, the voltage falls off as the current is increased. The amount of the falling off will depend on the design of the machine, and the lower the resistance of the armature, the better will be the voltage regulation. If the armature resistance is very low, a separately excited dynamo will fall off but little in voltage as the load is applied, and if it is necessary to keep the voltage absolutely constant, it can be done by increasing the field current.

SERIES-WINDING

84. There are three general methods by which self-excitation is accomplished. In the first, the whole of the current flowing through the armature also flows through the magnetizing coils; such a machine is said to be **series-wound,** from the fact that the armature and magnetizing coils are connected in series. This arrangement is represented in the diagram shown in Fig. 43.

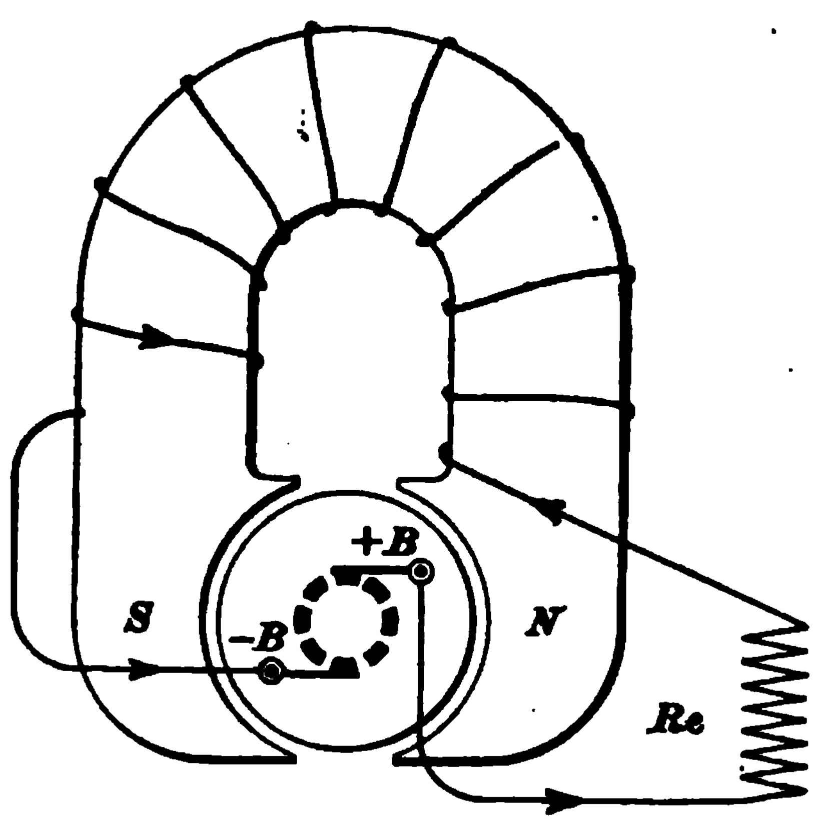


FIG. 43

With this arrangement, the magnetizing force acting on the magnetic circuit, consequently the number of lines of force in the magnet, varies with the current that the machine furnishes the external circuit; therefore, when the armature is running at a constant speed, the E. M. F. that is generated in it varies as the current varies, though not necessarily in the same proportion. This is not usually desirable, since most applications of direct current require that either the E. M. F. or the current be maintained approximately constant.

85. To realize either of the foregoing conditions in a series-wound dynamo, it is necessary to adopt some method of regulation, whereby either the effect of variations in the current on the magnetizing force of the field may be neutralized or the effective E. M. F. of the armature altered to suit the conditions. The former result may be obtained by placing an adjustable resistance in parallel with the magnetizing coil, as represented in Fig. 44. In this diagram, *S.F.* represents the magnetizing coil, or series-field, and *R* is the adjustable resistance, connected in

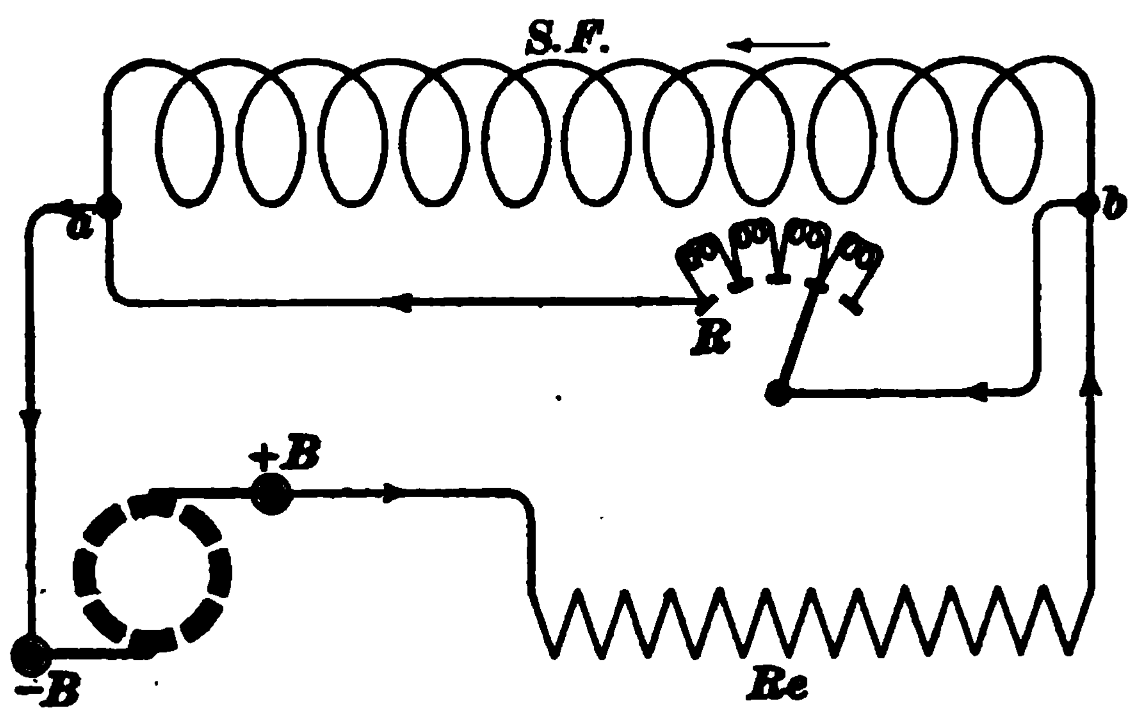


FIG. 44

parallel with the magnetizing coil, as described. It will be seen that the current divides between the two branches of this part of the circuit, and by varying the resistance *R* the proportion of the whole current that flows through the magnetizing coil *S. F.* may be varied as required. Other methods of varying the E. M. F. of series-wound dynamos intended for arc lighting will be described later.

86. Series-winding is very little employed in dynamos, except for machines designed to give a constant current, such as is used for operating lamps or other devices that are connected in series. For motors, however, series-winding is very useful, since when starting up under a heavy load, or whenever taking a current in excess of the normal amount,

the field strength is increased, which increases the amount of the reaction between the armature winding and the field, that is, increases the turning force of the armature.

87. Characteristics of Series Machine.—In the ordinary series dynamo it is evident that the voltage at the terminals of the machine will vary greatly with the current

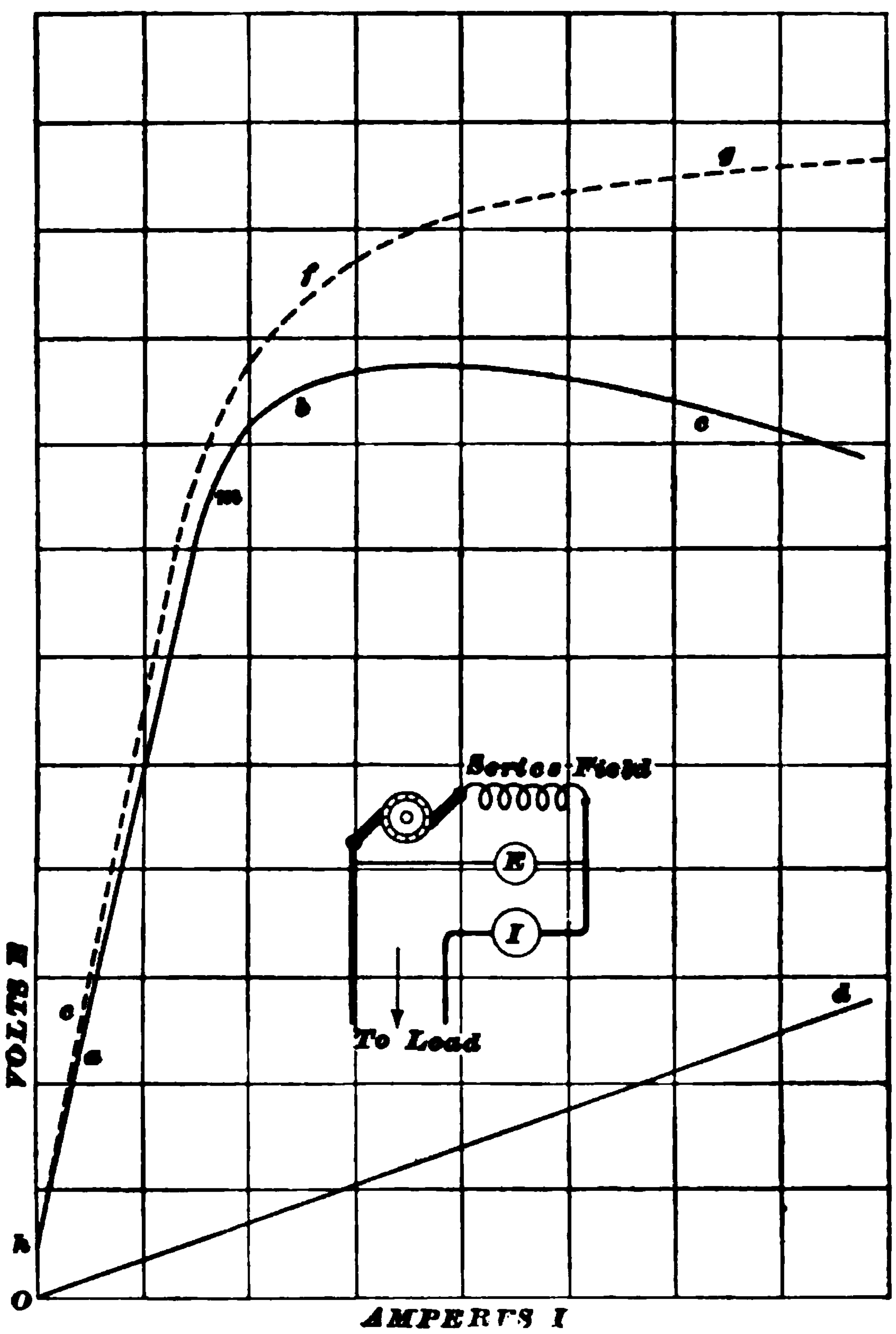


FIG. 45

output, because the current flows around the field coils, and every change in the current is accompanied by a corresponding change in the E. M. F. In Fig. 45, the curve *a b c* shows

the general shape of the external characteristic of a series-wound machine. If we draw the line $O d$ representing the volts drop in the armature and field and add its ordinates to those of the external curve, we obtain the total characteristic $e f g$, showing the relation between the load or current and the total voltage generated in the armature.

It will be noticed that the general shape of this total characteristic curve is similar to an iron magnetization curve. As the current increases, the voltage rapidly increases until a point is reached where the iron begins to saturate. The curve then bends off to the right and the increase in voltage becomes much smaller with the increase in current. Another point to be noted is that neither of the curves passes through point O, because, even when no current is flowing, the machine generates a small E. M. F. $O h$, due to the residual field magnetism. When the external resistance is such that the machine is worked on the straight part of the curve, say between h and m, its operation will be very unstable. For example, if the current decreased a little, due to a slight increase in the external resistance, the field magnetization and also the voltage would decrease by quite a large amount ; this would cause a still further decrease in the current, the final result being that the machine would drop its load. If, however, the external resistance is low enough so that the current magnetizes the field beyond the bend of the curve, the action will be stable because a reduction in current is not then followed by a large reduction in the E. M. F. For every series machine there is, therefore, a certain resistance for the external circuit which, if exceeded, will cause the operation of the machine to become unstable. This resistance is sometimes called the **critical resistance.**

In Fig. 45, it should be noticed that while the total characteristic keeps on rising slightly with the increasing current, yet the external characteristic drops after a certain point has been passed. This is because the increase in the armature drop more than offsets the slight increase in voltage due to the additional field ampere-turns.

SHUNT WINDING

88. The second method of self-excitation consists of forming a separate circuit of the magnetizing coils, which are connected directly between the brushes, or in shunt to the external circuit, this style of winding being, therefore, known as **shunt winding.** This is illustrated in Fig. 46.

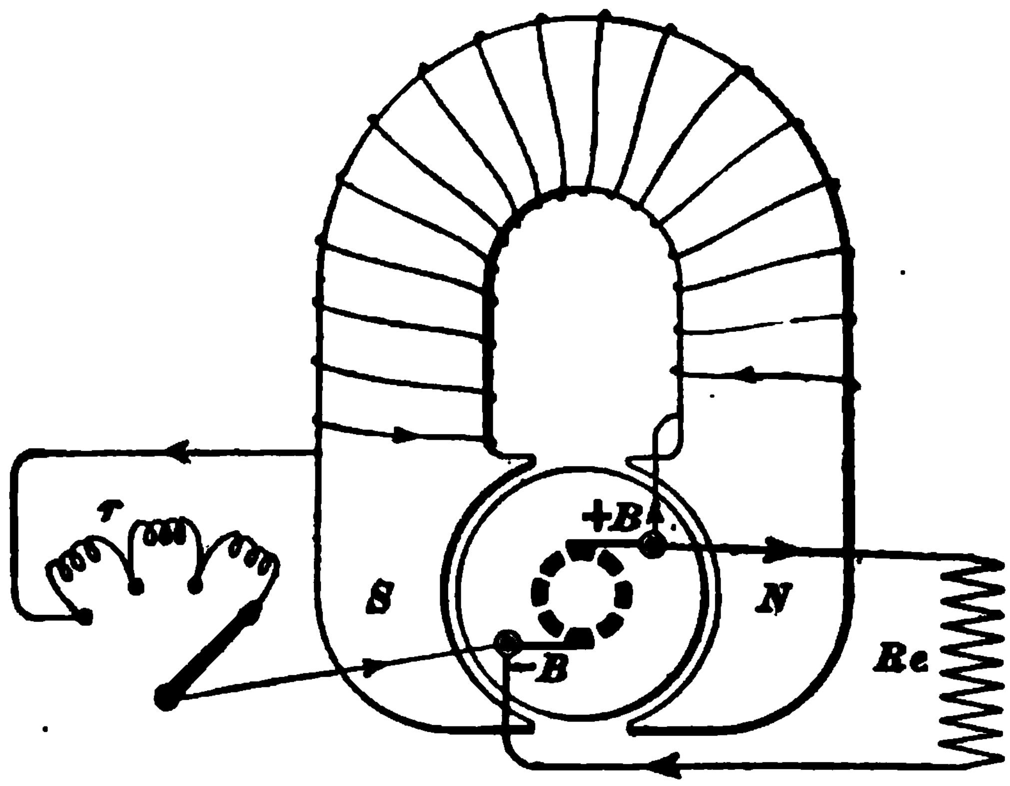


FIG. 46

It will be seen that the magnetizing-coil circuit is in a measure independent of the external circuit *Re*, it being exposed at all times to the full difference of potential that exists between the brushes $+B$ and $-B$; from this it follows that changes in the current flowing in the external circuit do not affect the magnetizing force acting on the field, except as they may change the difference of potential between the brushes. Changes in the current of the external circuit do affect this quantity in several ways; namely, by varying the drop due to the resistance of the armature winding, by varying the counter magnetomotive force of the armature winding, and by varying the length of the path of the lines of force by the variations in the amount by which they are distorted by the cross-magnetomotive force. This last is comparatively unimportant, but the other two require careful consideration in the design of dynamo machinery, as will be pointed out.

89. In a shunt-wound motor the conditions are different, the magnetizing-coil circuit being supplied directly from the mains ; the magnetomotive force then depends simply on the difference of potential between the supply mains, which is usually kept constant, so that in general a shunt-wound motor may be considered as having a constant magnetizing force acting on its field magnet.

90. Characteristics of Shunt Machine.—In the case of a shunt dynamo there are two characteristic curves that are commonly drawn in order to indicate the performance of the machine. One of these is called the **internal characteristic,** and shows the relation between the voltage at the brushes and the current in the field, or, perhaps, what is more usual, the ampere-turns on the field. In order to obtain this curve, the machine is run at a constant speed without load and its field is excited from an outside source, so that the current in the shunt coils can be varied from a small amount up to or above the full current for which they are intended. The voltage obtained at the brushes will at first increase almost in direct proportion to the field current, but as the iron becomes saturated the increase in E. M. F. for a given increase of field ampere-turns will become less. The internal characteristic curve, therefore, indicates at what current the field begins to saturate, and the general shape of the curve is the same as the dotted curve *h e f g*, Fig. 45.

91. The **external characteristic** of a shunt dynamo is quite different from that of a series dynamo, because the field current is to a certain extent independent of the current in the external circuit. Fig. 47 shows the general shape of the external characteristic; the curve *a b c d e* shows the relation between the voltage at the brushes and the current in the main circuit. The total characteristic *a g h* is found by adding the ordinates of *O k* to those of *a b c d e*. The full line part *a b c* of the external characteristic represents the actual working range of the machine, assuming that *O f* represents the full-load current. At no-load, zero current,

the voltage at the brushes is represented by the vertical *O a*. This is the maximum voltage that the machine is capable of giving with a given field excitation, because the pressure across the field coils is a maximum; as soon as current is taken from the armature, the pressure across the fields decreases and there is also a drop in the armature, hence the voltage decreases. It is evident that a shunt machine can generate its full voltage even if the external circuit is open

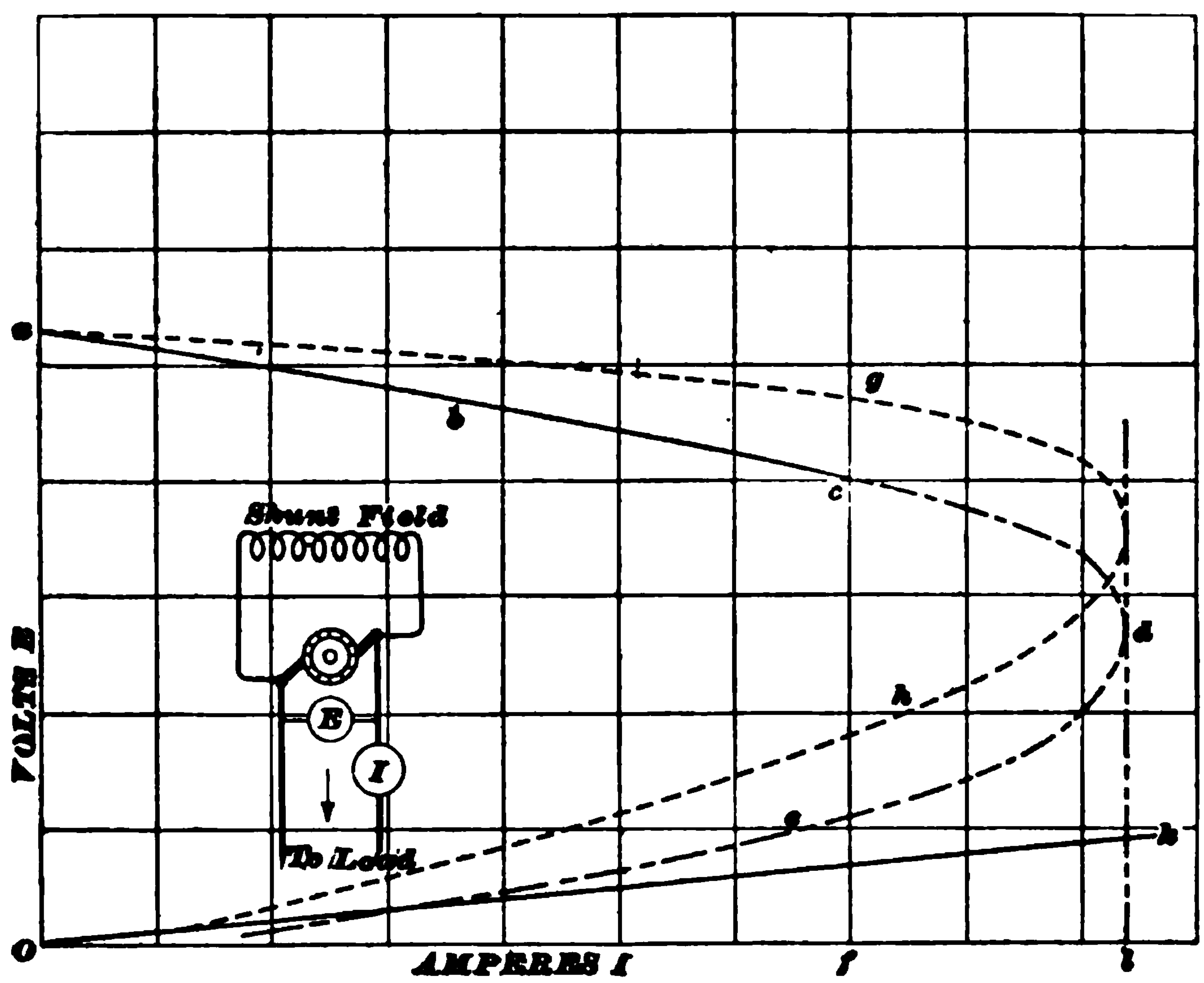


FIG. 47

because the path through the magnetizing coils is not interrupted as it is with the series dynamo. As the current is increased from no load to full load, the terminal voltage drops from *O a* to *f c*. In this respect the shunt dynamo behaves somewhat like a separately excited machine, but the falling off in voltage with a given machine would be greater with shunt excitation than with separate excitation. The reason for this is, of course, that with the separately excited machine the pressure applied to the field coils is constant, whereas, with the shunt dynamo every falling

off in terminal pressure causes a decrease in the field excitation.

92. If the external resistance is made low enough, the current will reach such a value, represented by $O\,l$, that the pressure across the shunt terminals becomes so low that the unstable portion of the magnetization curve is reached. When this is the case, any further decrease in terminal voltage causes the machine to drop its voltage entirely, the unstable portion of the characteristic curve being represented by the dot-and-dash part $d\,e$. In well-designed shunt machines, this unstable condition is not usually reached until the current is considerably greater than the full-load rating of the machine. For example, in the case shown in Fig. 47 the working range of current is from O to f, and the action would not become unstable until the current increased to l. A peculiarity of the shunt machine is, therefore, that the external resistance must be above a certain critical value in order for the machine to generate. For example, a shunt machine, if short-circuited, will drop its voltage. This is just the opposite to a series machine, where the external resistance must be below a certain critical value in order to allow the machine to pick up its voltage, and in case of a short circuit on a series dynamo, the voltage rises very rapidly.

93. If the armature of a shunt dynamo has a very low resistance and the field a high resistance, the curve $a\,b\,c$ will drop but little, and the machine will, therefore, hold its voltage fairly constant within the working range. The smaller the slant of $a\,b\,c$, the greater must be the external current before the voltage becomes unstable. The falling off in voltage can be compensated for by cutting out some of the resistance in the shunt field, so that by resorting to the rheostat the line $a\,b\,c$ can be made horizontal or even rise a certain amount as the load comes on. This method of regulation is feasible when the load does not vary suddenly, but where a constant potential is desired it is now customary to use compound-wound machines.

COMPOUND WINDING

94. From the foregoing statements it will be seen that in order to maintain a constant difference of potential between the brushes of a dynamo (assuming a constant speed), the magnetomotive force of the magnetizing coils must be increased as the current increases, both to increase the number of lines of force so as to increase the E. M. F. generated, and to make up for the counter magnetomotive force of the armature winding. One way to accomplish this result is to place an adjustable resistance *r*, Fig. 46, in the magnetizing-coil circuit, which may be gradually cut out as the current output increases, thus reducing the resistance of the magnetizing-coil circuit, and increasing thereby the current flowing through it. This, however, requires personal attention, and in case the current from the dynamo fluctuates rapidly, it is difficult to operate the resistance with sufficient rapidity. Since the amount by which the magnetomotive force of the magnetizing coils must be varied is closely proportional to the current flowing, which follows from the nature of the causes that require the variation, it is possible to obtain the required variation by providing additional magnetizing coils through which the main current passes. This is known as **compound winding,** and is illustrated in Fig. 48.

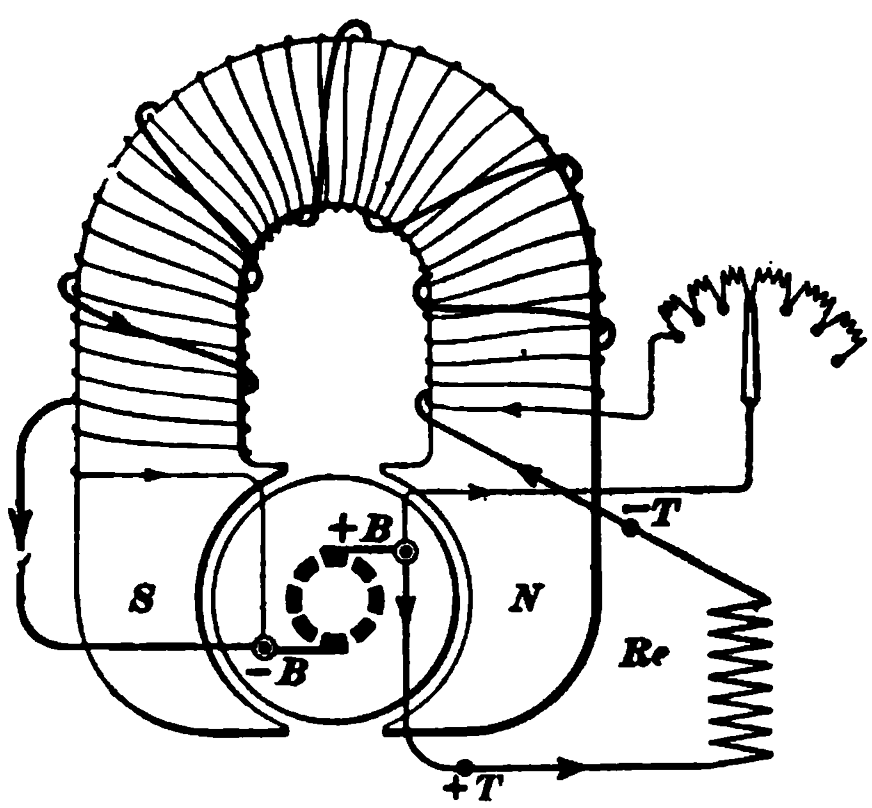


FIG. 48

95. It is evident that this is a combination of series and shunt winding, the shunt winding furnishing an approximately constant magnetizing force and the series-winding an additional magnetizing force that is proportional to the

current output of the machine. This latter winding is so proportioned that it furnishes the proper increase in the magnetomotive force, as the current increases, to make up for the dropping off of the difference of potential between the brushes that would otherwise occur. For certain classes of work, a little more than this amount is provided, so that the difference of potential between the brushes rises slightly as the current output increases. In such a case the machine is said to be **over-compounded.** Compound-wound machines are provided with a rheostat in the shunt field, but this rheostat is not intended for regulating the voltage in the sense that it is used with a plain shunt machine. The rheostat is intended to allow an initial adjustment of the voltage, thus compensating for any departure from the standard speed or for variation in the quality of the iron in the magnet frame. Also the shunt winding heats up after the machine has been in operation for a while and this heating raises the resistance, thereby cutting down the magnetizing current. If a rheostat is included in the field circuit this can be compensated for by cutting out some of the resistance after the machine has become warmed up. The series-winding, however, compensates for all changes in the voltage due to changes in the load.

96. Compound winding is not used nearly so often for motors, since either a series or a shunt winding serves for almost all conditions of operation. Nevertheless, for application to such machinery as printing presses, a compound winding is extremely useful, as the series-turns produce a powerful field at starting and at slow speed, and they may gradually be cut out or connected in various combinations to produce different working speeds without the necessity of inserting an external resistance in the armature circuit, except for starting up, when a resistance may be temporarily used.

97. Characteristics of Compound-Wound Machines. The characteristic of a compound-wound dynamo will depend very largely upon the magnetizing effect of the series-coils.

The coils may be strong enough to overcompound the machine, in which case the external characteristic would take the form of a rising line *a d e*, Fig. 49. If the series-coils were just strong enough to keep the terminal voltage constant, the characteristic would become a horizontal line *a c*. If the series-coils were not powerful enough to compensate for the falling off in voltage, the characteristic would drop as shown by *a f*, but the dropping would not be

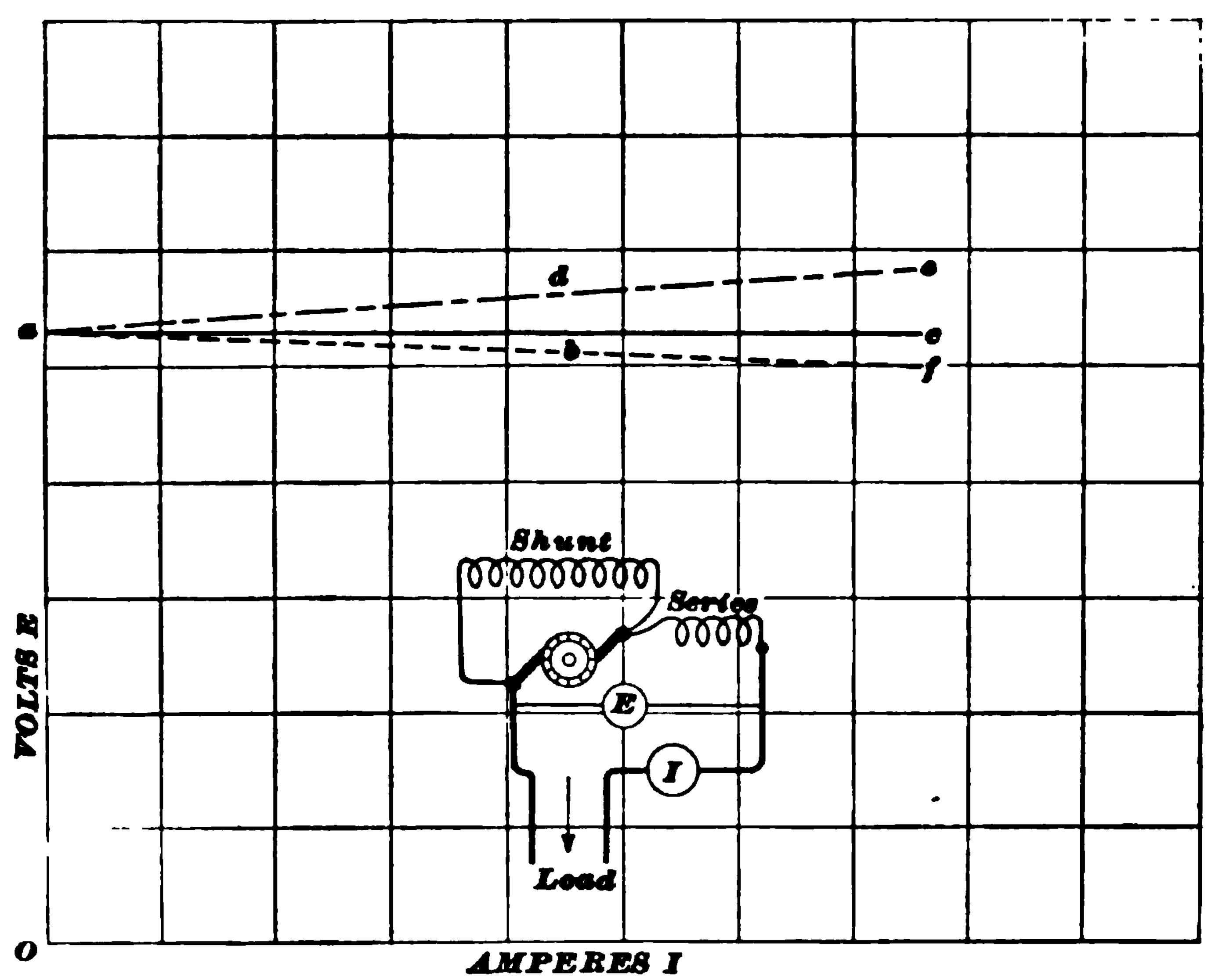


FIG. 49

as great as for a plain shunt machine. Usually compound-wound machines are wound to give a rising characteristic so that if the external resistance is lowered very greatly, as by a short circuit, the effect is to put a very heavy overload on the machine because the voltage will not drop on short circuit as with a shunt dynamo. In connecting up the series-coils of a compound-wound machine, care must be taken to see that they are connected so as to aid the shunt coils and not oppose them, because in the latter case the machine would drop its voltage as soon as a load came on.

BUILDING UP THE FIELD

98. Any iron, after being magnetized, retains a certain amount of residual magnetism, so that there will be a small E. M. F. generated in the armature winding when the armature is rotated and the field circuit left open; this is utilized to start the current in the magnetizing coils. In the case of a shunt-wound dynamo, when the machine is started and the magnetizing-coil circuit closed, the small E. M. F. generated in the armature by the residual magnetism sends a small current through the magnetizing coils, producing a small magnetizing force. If this magnetizing force tends to send lines of force through the magnetic circuit in the same direction as the residual magnetism, the number of lines of force will be increased; this will increase the E. M. F., which increases the current in the magnetizing coils, and still further increases the number of lines of force and the E. M. F., which process continues until further increase in the magnetizing force results in so little increase in the number of lines of force that the E. M. F. generated becomes steady, the windings being so designed that this shall be the E. M. F. at which it is desired to run the machine.

It will be seen that if the external circuit is open, all the current that the E. M. F. (due to the residual magnetism) produces flows through the magnetizing coils; if, however, the external circuit is closed, only a part of the current flows through the magnetizing coils, so that the field will build up more slowly than with the external circuit open, and, in fact, will not build up at all if the external resistance is low, as compared with the armature resistance. From this it follows that a shunt-wound machine should be started up with its external circuit open.

A series-wound machine, on the contrary, must have its external circuit closed in order that any current may flow through the magnetizing coils, and the lower the resistance of the external circuit, the more quickly will the machine build up.

From the above it will be seen that a compound-wound dynamo may be started with its external circuit either open or closed, since it has both series and shunt wound coils. Usually, however, such machines are started and brought to their full E. M. F. with the external circuit open.

99. At starting, while the current is increasing in the magnetizing-coil circuit, the self-induction of the magnetizing coils increases their apparent resistance, and a part of the energy supplied to the coils is stored up in the magnetic field that is being established. As soon as the current in the magnetizing coils reaches its maximum value, however, and so long as it remains constant at this value, the entire amount of energy delivered to the coils is expended in heating the wire; that is, it requires (directly) no energy to maintain a magnetic field at a constant value, the field depending on the number of ampere-turns that are acting on the magnetic circuit. It is obvious, however, that in order to force the current through the wire of which the magnetizing coil is composed, energy must be expended, but this energy appears entirely as heat, and, consequently, is wasted as far as any practical application of it is concerned. The number of watts expended in sending the current through the magnetizing coils should, therefore, be made as small as the design of the machine will permit, both to prevent any excessive waste of energy and to prevent possible damage by the heat liberated. In practice, the loss of energy from this cause varies from about 1 per cent. of the total output of the machine in larger sizes, to 5 per cent. or more in the smaller.

100. In shunt-wound machines the magnetizing coils are exposed to the full difference of potential that exists between the brushes of the machine, and, consequently, should use only a small amount of current in order that the loss in watts may be the required small percentage of the output. From this it follows that the wire used for the magnetizing coils should be of small size and of considerable

length, making a large number of turns around the magnets, both to give the necessary resistance to keep the current at its proper value and to allow of this small current furnishing the requisite number of ampere-turns. In series-wound machines, however, as the total current flowing gives the magnetizing force, the magnetizing coils need to have comparatively few turns, which should be of correspondingly large wire, in order that the watts loss (equal to I^2R) should be kept within the desired limits.

It will be seen that in series-wound dynamos the difference of potential between the terminals of the machine is less than that which appears between the brushes by the amount of the drop in the magnetizing coils.

The above remarks concerning the magnetizing coils of shunt and series wound dynamos also apply to those of compound-wound machines, since they are made up of a shunt-winding and a series-winding.

DYNAMOS AND DYNAMO DESIGN

(PART 2)

DIAGRAMS OF CLOSED-COIL WINDINGS

RING WINDINGS

1. Ring windings are not much used in modern machines, although the single multicircuit ring winding has advantages that make it quite prominent for generators producing high voltages on one hand, or very large currents on the other. This winding, arranged in a four-pole field magnet, is shown in Fig. 1. It will be noticed that there are two turns per coil, and that the winding is represented as continuous, leads being tapped in for connecting to the commutator. Such construction is exactly equivalent, electrically, to that where the ends of each coil are brought down to the commutator. The latter method, however, is preferable to the former, because the connections are more easily made at the commutator.

2. To connect the machine to the outside circuit, the two positive brushes should be connected together to form the positive terminal, and the two negative brushes in the same manner to form the negative terminal. The direction of flow of the armature currents is shown in the four

paths. It will be observed that in each neutral region a single armature coil is short-circuited by a brush, and therefore has no current in it, as indicated by the absence of the arrowheads. Under the north poles it is found that the arrowheads point inwards, while under the south poles they point outwards; of course these conditions would be exactly interchanged were the direction of rotation reversed.

3. Comparing Fig. 12 of Part 1 with Fig. 1, it will be noticed that they are very similar as far as the winding of the coils is concerned, the only difference being in the number of coils on the complete armature. Were the armature of Fig. 1 put in a six-pole or an eight-pole field magnet, it would not be necessary to alter anything connected with the winding in the least degree, but the brushes, of course, would have to be the same in number as the poles. It follows that an armature provided with this winding may be used in a field frame with any number of poles. While this is an interesting feature possessed by no other winding but the multicircuit ring type, it is of little commercial importance, as it is very unusual to have occasion to use an armature in several machines having different numbers of poles.

FIG. 1

4. In Fig. 1 there are thirty-two coils on the armature, or eight between brushes of opposite signs. Suppose that these coils were wound to generate 100 volts each; then, since

there are seven active ones between brushes, the machine would deliver about 700 volts. It will be observed that the coils connected to one set of brushes are separated by a considerable distance on the armature from those connected to the other set. In fact, the extreme E. M. F. between one coil and its neighbors can be only that developed by the one coil. To insulate such a coil from others does not require very thick insulation, and with each coil insulated, the complete winding will be successfully insulated. Thus, to insulate each coil to withstand 100 volts between it and its neighbor, will successfully insulate the complete armature for a pressure of 700 volts. This is a great advantage that ring windings with a single coil in series between segments have over drum types, for in the latter the coils overlap one another, and the room required for insulation, were these windings used for several thousand volts, would make the complete armature bulky and cumbersome. On account of the ease with which they can be insulated for high pressures, ring windings are much used for series arc-lighting dynamos.

5. In machines intended for generating very large currents, as, for instance, large, direct-current, 125-volt generators, it is found necessary, in order to prevent sparking, to use as many commutator segments as possible. The greatest number of segments possible is one segment per turn; on a ring armature a turn includes but one face conductor, while for a drum armature it includes two face conductors.

It will be shown later that the voltage depends on the number of face conductors in series; so with the same voltage, i. e., the same face conductors, a ring winding may have twice as many segments as can be used for the drum type.

Ring windings have a further advantage that, since the coils do not overlap one another, any coil or coils may be removed without disturbing any others, and reinsulated or replaced by new ones, if necessary.

DRUM WINDINGS

PARALLEL WINDINGS

6. Diagrams of **drum windings** are far more complicated than those for ring windings, and it is necessary to adopt some conventional way of representing them. The method that will hereafter be used is shown in Fig. 2, which

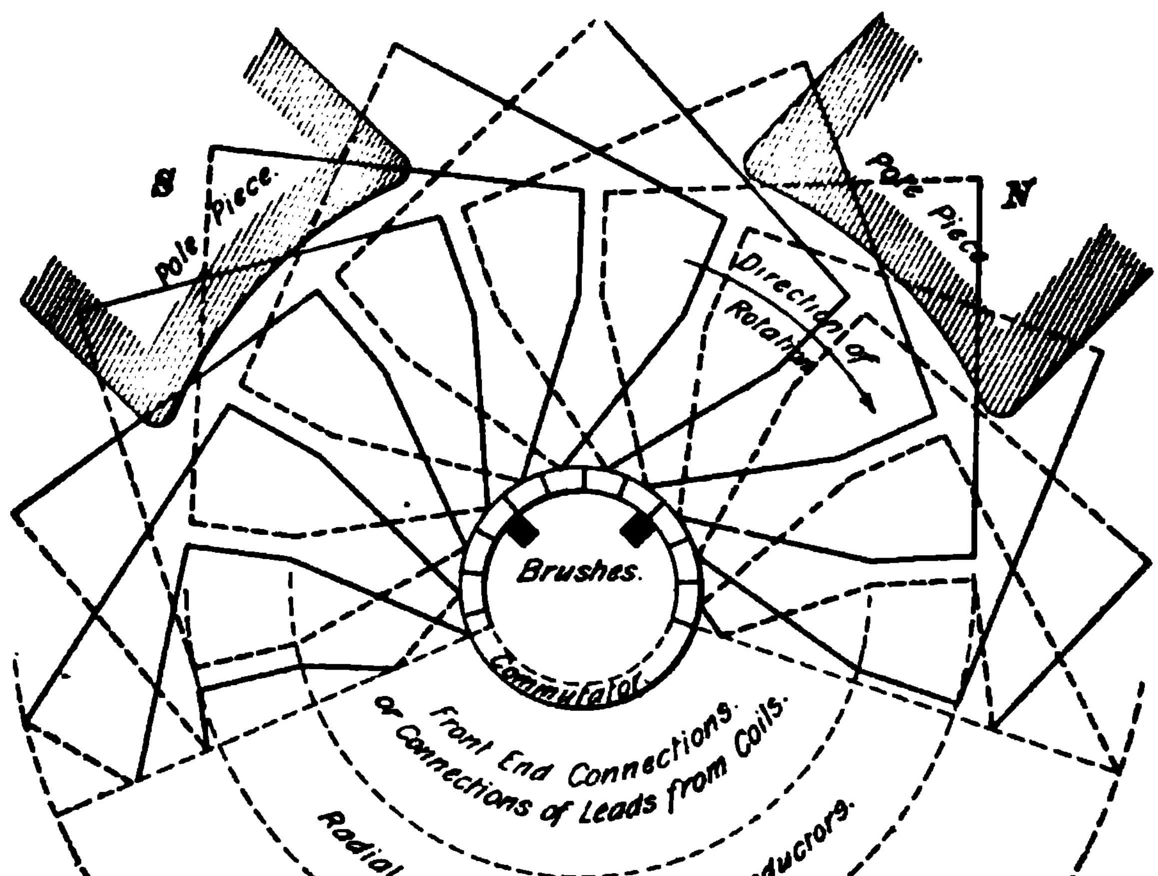
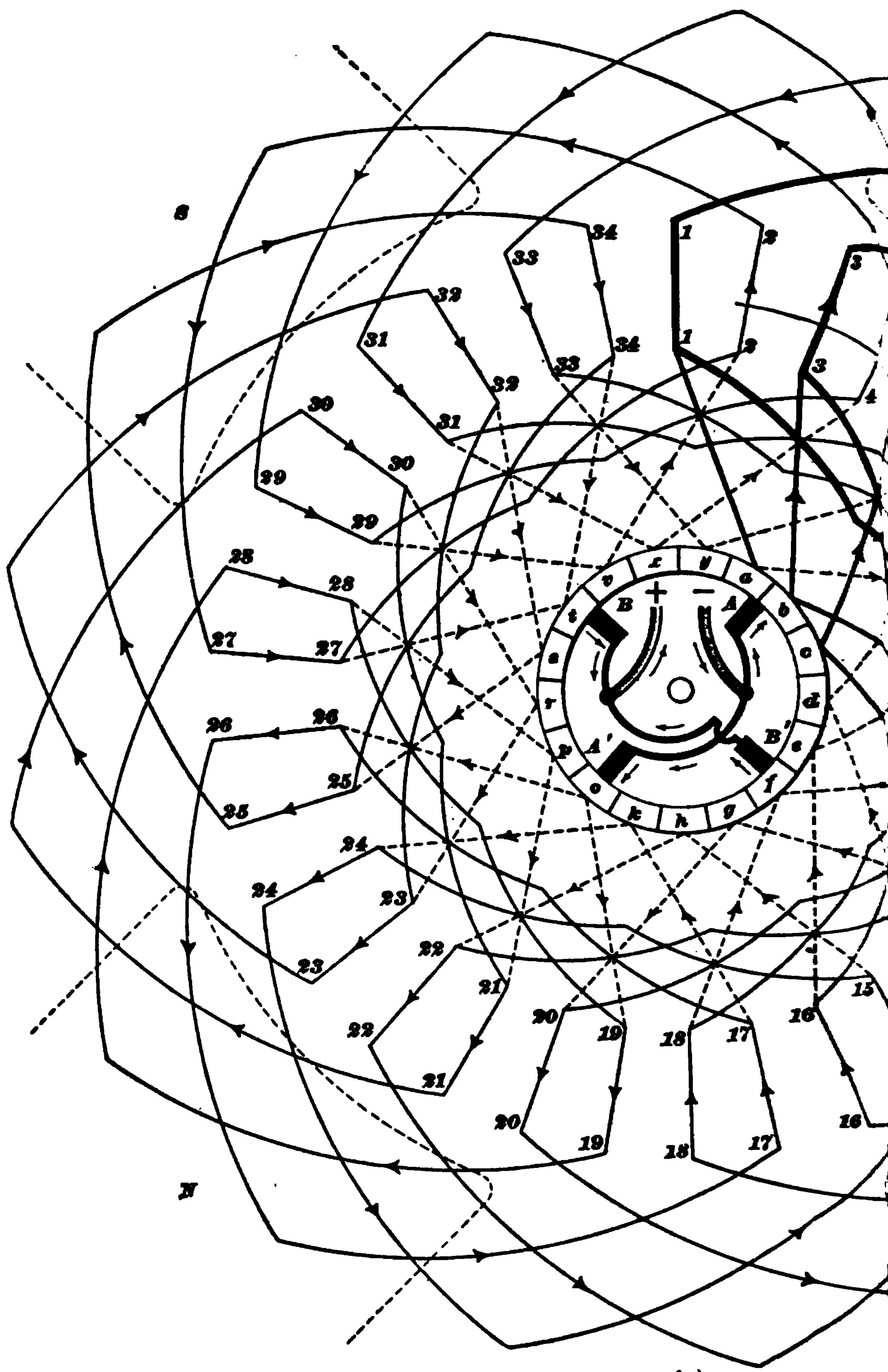


FIG. 2

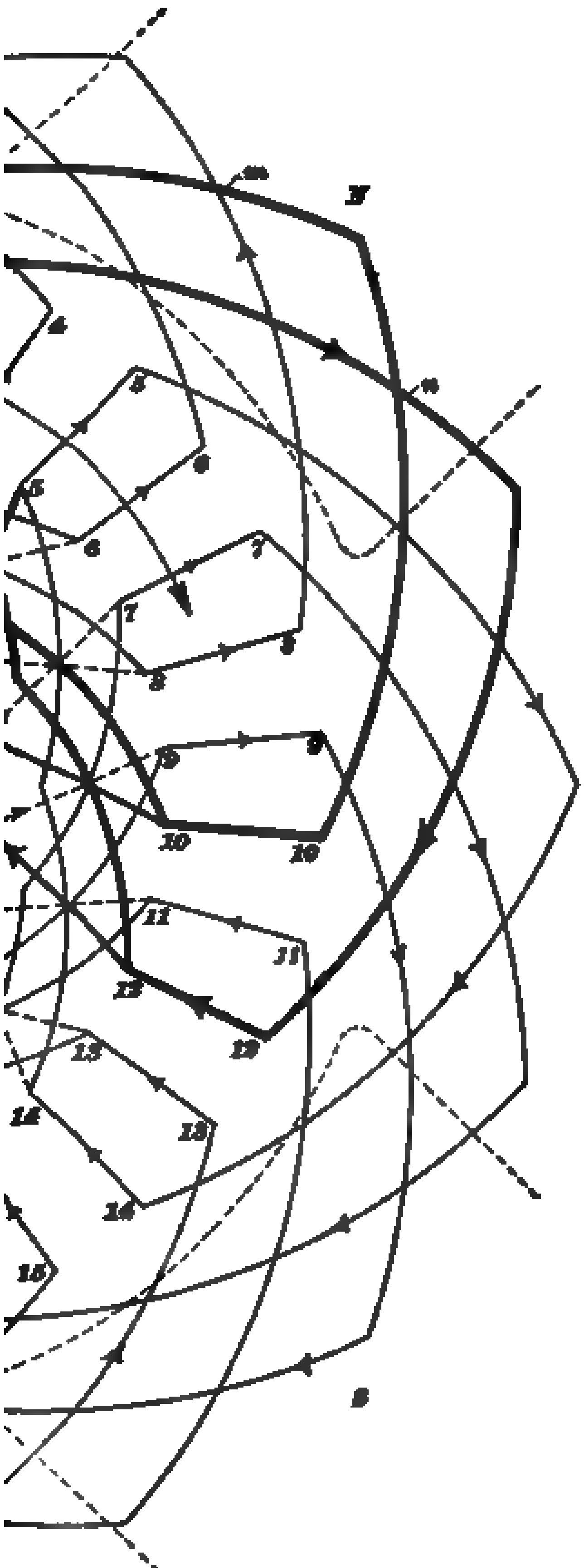
explains itself. The face conductors are here shown as short radial lines outside of which are the rear end connections; the position of the poles is indicated as shown. Inside of the radial lines are shown the front end connections and leads to the commutator, inside of which are the commutator and the brushes. As inferred above, the commutator end of an armature is called the **front end.**

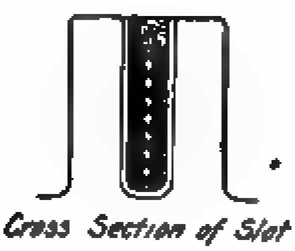
Almost all modern electric generators of 50 kilowatts, or more, output have but a single turn to a coil, and in many



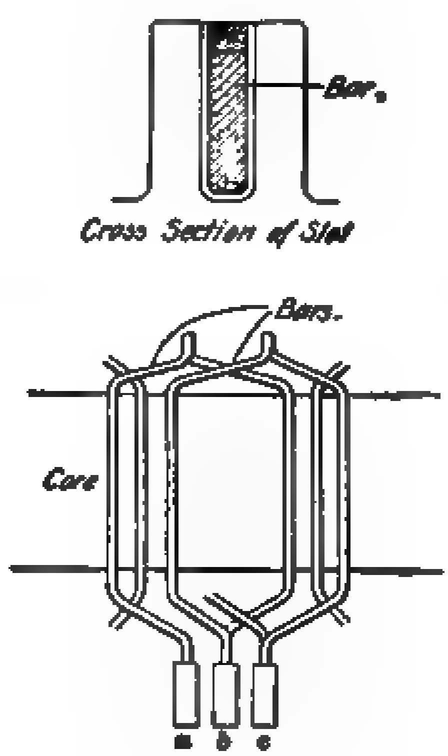
(a)

Fi




Cross Section of Slot.

(b)


Bar.
Cross Section of Slot
Bars.
Core
a b c

(c)

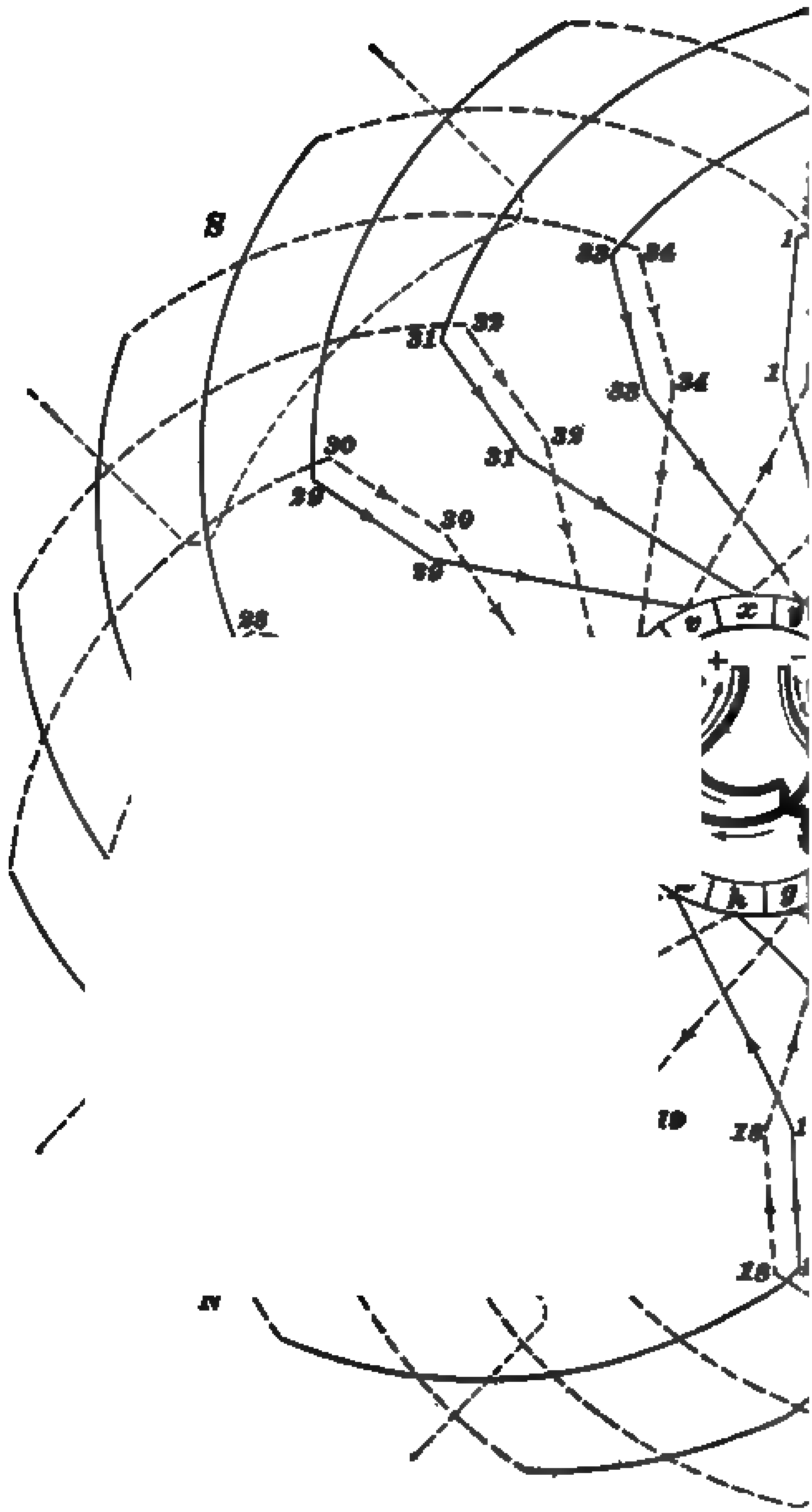
cases, instead of using round copper wires, rectangular bars are used and the windings thus made are termed **bar-wound,** to distinguish them from those that are **wire-wound.** Where the output of a generator is made the greatest possible, in order to be economical of material, the available room for the windings scarcely permits the use of round wires on account of the waste space left between wires, and the bar winding must then be used. Bar windings are sometimes used with coils of two or more turns each, but very rarely, as the coils with more than one turn are hard to handle, when made of large copper conductors, and besides it is seldom that a machine requiring large bars for conductors also requires a two-turn winding.

7. Fig. 3 is a diagram of a four-pole, single, parallel, drum winding with seventeen coils, seventeen commutator segments, and thirty-four slots. The complete diagram is shown at (*a*), while the details of a slot and a sketch of a wire-wound coil are shown at (*b*) and the same for a bar-wound coil at (*c*). It will be noticed that the current comes in through brushes *A*, *A'* and goes to segments *a*, *b*, and *o*. To *a* is connected one lead, or terminal, of coil *1–10*, the other end of which is connected to segment *b*. This coil is short-circuited by the brush *A* and has no current in it at the instant shown. The face-conductors of coil *1–10* are about midway between the poles or in the neutral region. From *a* is connected another coil *8–33*, which terminates at *y*, where, also, connects coil *6–31*, etc. Thus one of the paths is *a*,*–8–33* to *y*, *6–31* to *x*, *4–29* to *v*, *2–27* to *t*, where it touches positive brush *B*. In the same way another path is from *b* to coil *3–12* to *c*, *5–14* to *d*, *7–16* to *e*, *9–18* to *f*, and thence to positive brush *B'*. There is also a path that includes the segments from brush *A'* to *B* and a path including segments from *A'* to *B'*. The winding is seen to have four paths or as many as there are poles, and there are four coils in series in each path. The face conductors carry the current away from the commutator under north poles and toward the commutator under south poles.

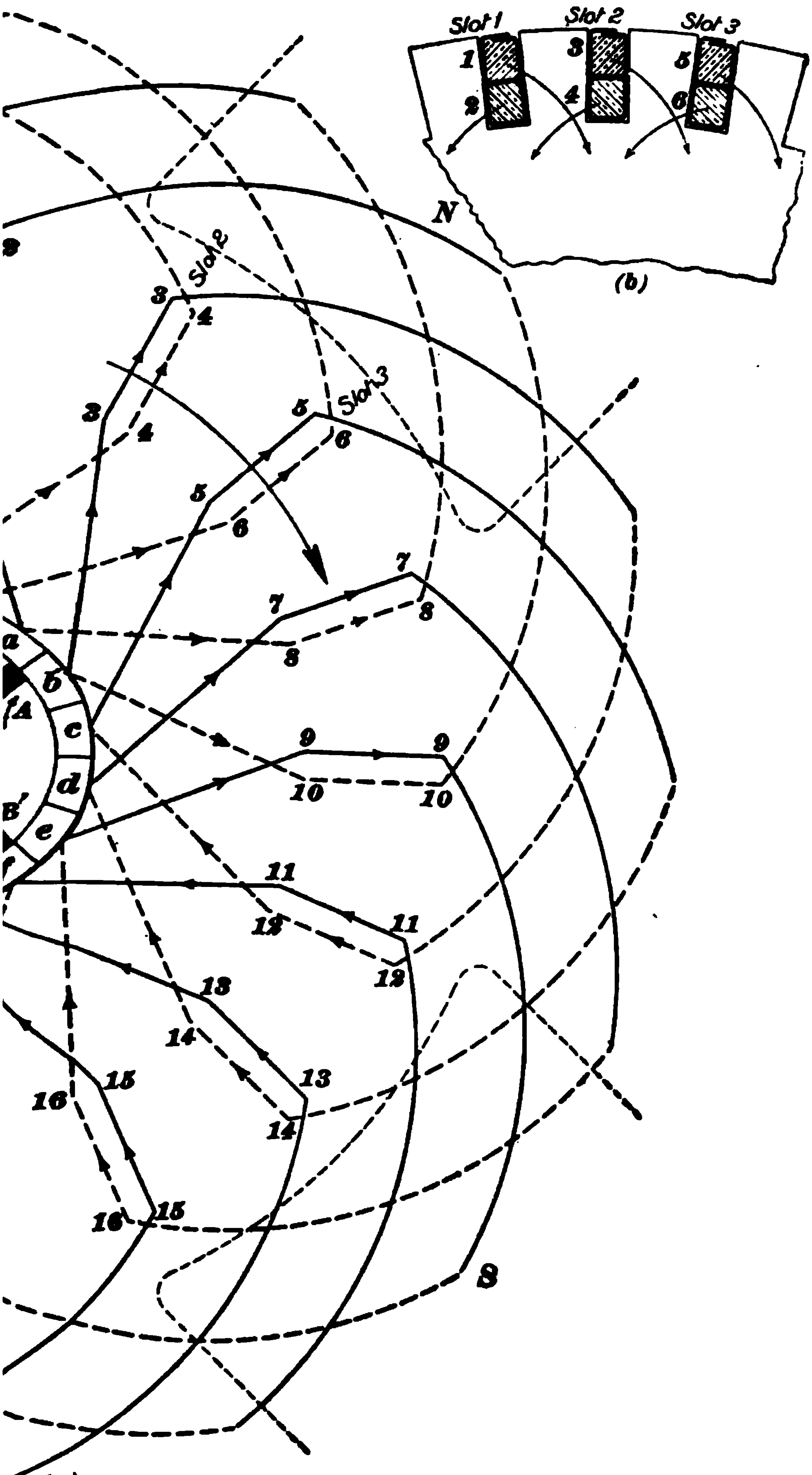
This is the reverse of the winding shown in Fig. 1, the reason being that the direction of rotation is reversed. The paths and the direction of currents in the windings should be carefully studied until thoroughly understood.

8. In following out the various paths, it will be observed that the end connections of the coils on the commutator end are not essential to determining a path, and since they confuse the diagram, it is usual to omit them. This makes the diagram appear as though the coils were of a single turn only, and in the diagrams following they will be drawn this way, it being understood that the diagram of the winding is exactly the same, regardless of the number of turns per coil.

It is seen from Fig. 3 that the position the brushes occupy on the commutator with regard to the pole pieces depends on the way in which the terminals of the coils are connected. For example, take the lead *1–a* that connects from slot *1* to bar *a*. If this lead were brought out to the bar directly in front of the slot, then the brushes *A*, *B*, *A'*, *B'* would, when in the neutral position, be opposite the center of the space between the poles. This would, however, necessitate one long terminal and one short terminal on each coil, because the terminal *10–b* would have to be long enough to reach around to the bar adjacent to that opposite slot *1*. It is usual, therefore, to bring the coil leads, when connecting them to the commutator, around through an angle of about one-half the pitch of the poles. For example, in Fig. 3, the lead *1–a* is brought around to the right through an angle of about one-eighth a circumference, thus bringing the brushes opposite the centers of the pole pieces when in the neutral position. This arrangement makes the coil terminals *1–a* and *10–b* of about equal length and renders the connections symmetrical. Bringing the coil terminals around in this way is termed *giving them a lead*, and it is evident that the neutral position of the brushes will depend on the lead. For some kinds of railway motors, one coil terminal is brought out straight, so that each coil has one long terminal and one short one; but with nearly all generators the coil terminals



Fi


Slot 1
Slot 2
Slot 3
1
2
3
4
5
6
N
S
a
b
c
d
e
f
A
B'
7
8
9
10
11
12
13
14
15
16
(b)
(a)

4

are brought around through an angle of about one-half the pole pitch, and the neutral position of the brushes at no load is nearly opposite the center of the pole pieces.

9. At (*b*), Fig. 3, is shown the details of a wire-wound coil and the cross-section of a slot. The slot is first lined with insulating material, then the coil is put in place, and lastly a piece of wood is usually inserted over the coil to protect it. Coils *1–10* and *3–12*, the ones that are shown in heavy lines at (*a*), are shown inserted in the slots in the core with their leads properly connected to the commutator segments *a*, *b*, *c*. At (*c*) the same slots are shown, each occupied by a single, rectangular, copper bar instead of a number of wires, as at (*b*). The same coils are shown connected to the segments *a*, *b*, *c*. Comparing (*b*) and (*c*), it will be noticed that the latter is much simpler in appearance, for the coils, consisting of but a single turn, have no end connections on the front, or commutator, end, as do the coils (*b*).

10. Suppose that all the coils were connected to the commutator thus: connect *1* to segment *b* and *10* to segment *a*, *3* to segment *c* and *12* to segment *b*, etc.; in other words, if the leads of each coil were interchanged, what effect would it have on the action of the winding? It would still be a single parallel winding, since the coils terminate in adjacent segments and the E. M. F. generated in the coils would be the same in direction and amount; but since each coil has had its leads reversed, the E. M. F. of the completed armature would be reversed and the brushes A and A' would become positive brushes, while B and B' would become negative brushes. Each lead would have to be a little longer than before and, therefore, more copper would be required; such a winding would therefore be objectionable on this account.

11. It will be noticed in Fig. 3 that at either end of the core the coils extend both to the right and to the left. As has been explained, the cross-connections interfere with one another unless involute end connections are used, and in order to avoid this it is usual to make the winding in two

layers, placing two coils in each slot, one on top of the other, so that all those in the bottom extend to the right, say, while those at the top extend to the left. Such windings are called **two-layer windings,** while that of Fig. 3 is called a **single-layer winding.**

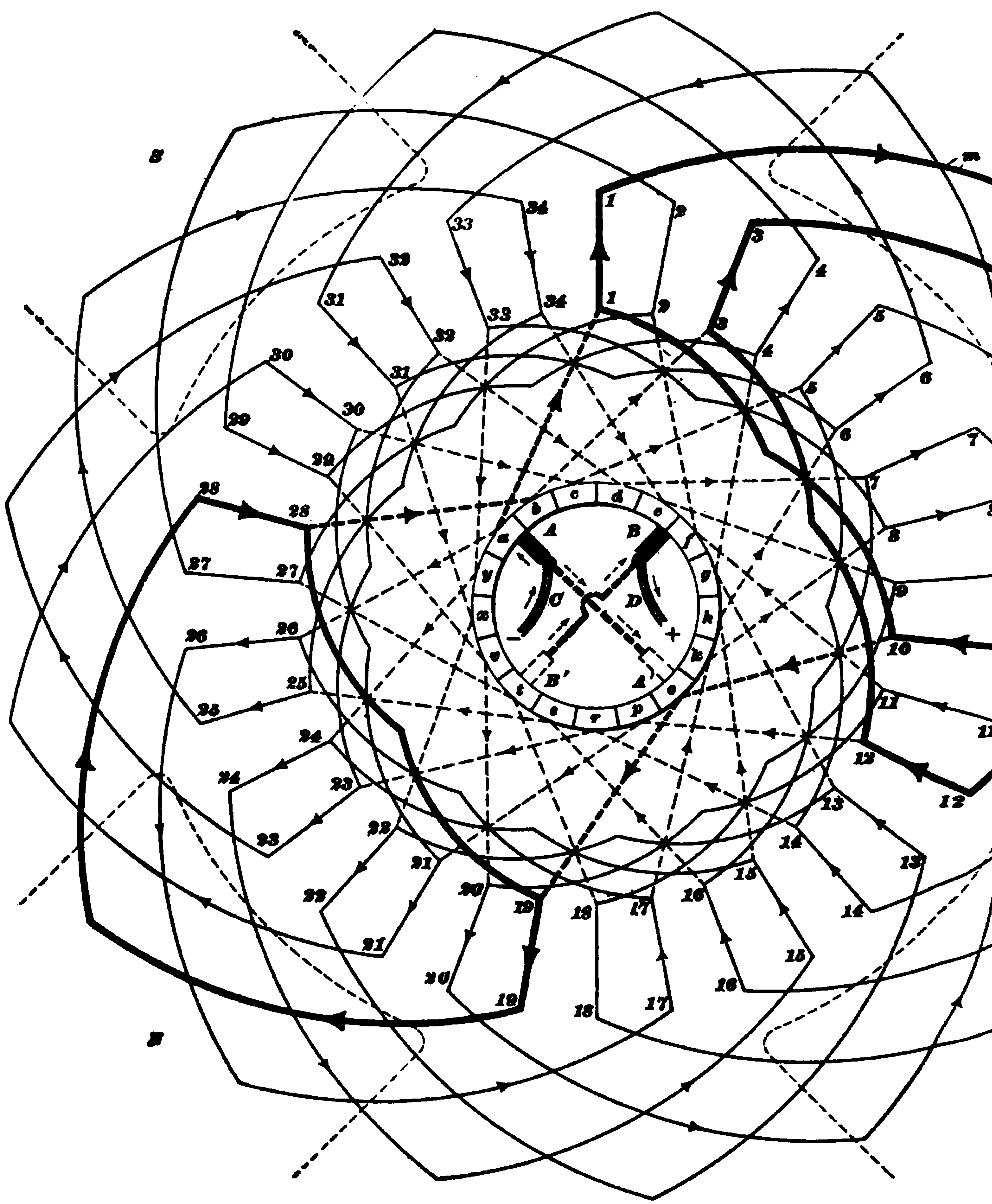
In Fig. 4 is shown a two-layer winding of one turn per coil, the exact electrical equivalent of Fig. 3, but having only seventeen slots instead of thirty-four.

12. In Figs. 3 and 4 notice that at the instant shown coil *1–10* ends in segments connected to the negative brush *A*, hence is at the potential of *A*; likewise for the same reason coil *27–2* is at the potential of positive brush *B*, so that the potential difference between these two coils is equal to that developed by the machine at the instant shown. Conductors *1* and *2*, between which there exists this large potential difference, are adjacent in both diagrams, being in the same slot in Fig. 4. It will be noticed that this is a necessary property of drum windings and may be stated thus: Between adjacent coils of a drum-armature winding at times during a revolution there exists the full potential of the machine. This constitutes the chief objection to drum windings, and necessitates that extra-good insulation be provided between the coils in the slots [see (*b*), Fig. 4]. Observe that the extreme difference of potential also exists between conductors *33* and *34*, *11* and *12*, *19* and *20*, and *27* and *28*. In general, it may be said that the extreme differences of potential will exist between one coil of one layer and its neighbor in the other layer at the time of commutation.

13. In Fig. 4, the paths or circuits from negative to positive brushes are as follows:

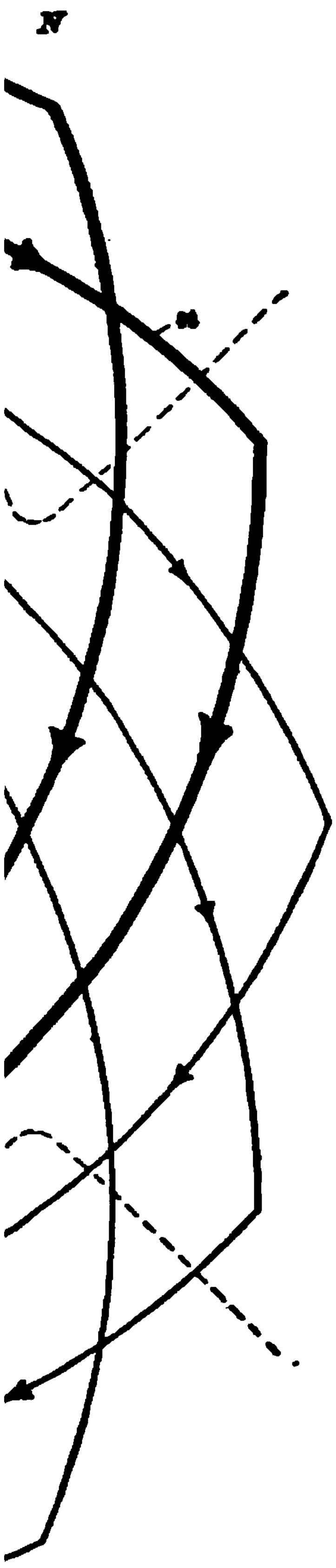
$$- \left\{ \begin{array}{l} A,\ 3\text{–}12,\ 5\text{–}14,\ 7\text{–}16,\ 9\text{–}18,\ B' \\ A,\ 8\text{–}33,\ 6\text{–}31,\ 4\text{–}29,\ 2\text{–}27,\ B \\ A',\ 19\text{–}28,\ 21\text{–}30,\ 23\text{–}32,\ 25\text{–}34,\ B \\ A',\ 26\text{–}17,\ 24\text{–}15,\ 22\text{–}13,\ 20\text{–}11,\ B' \end{array} \right\} +$$

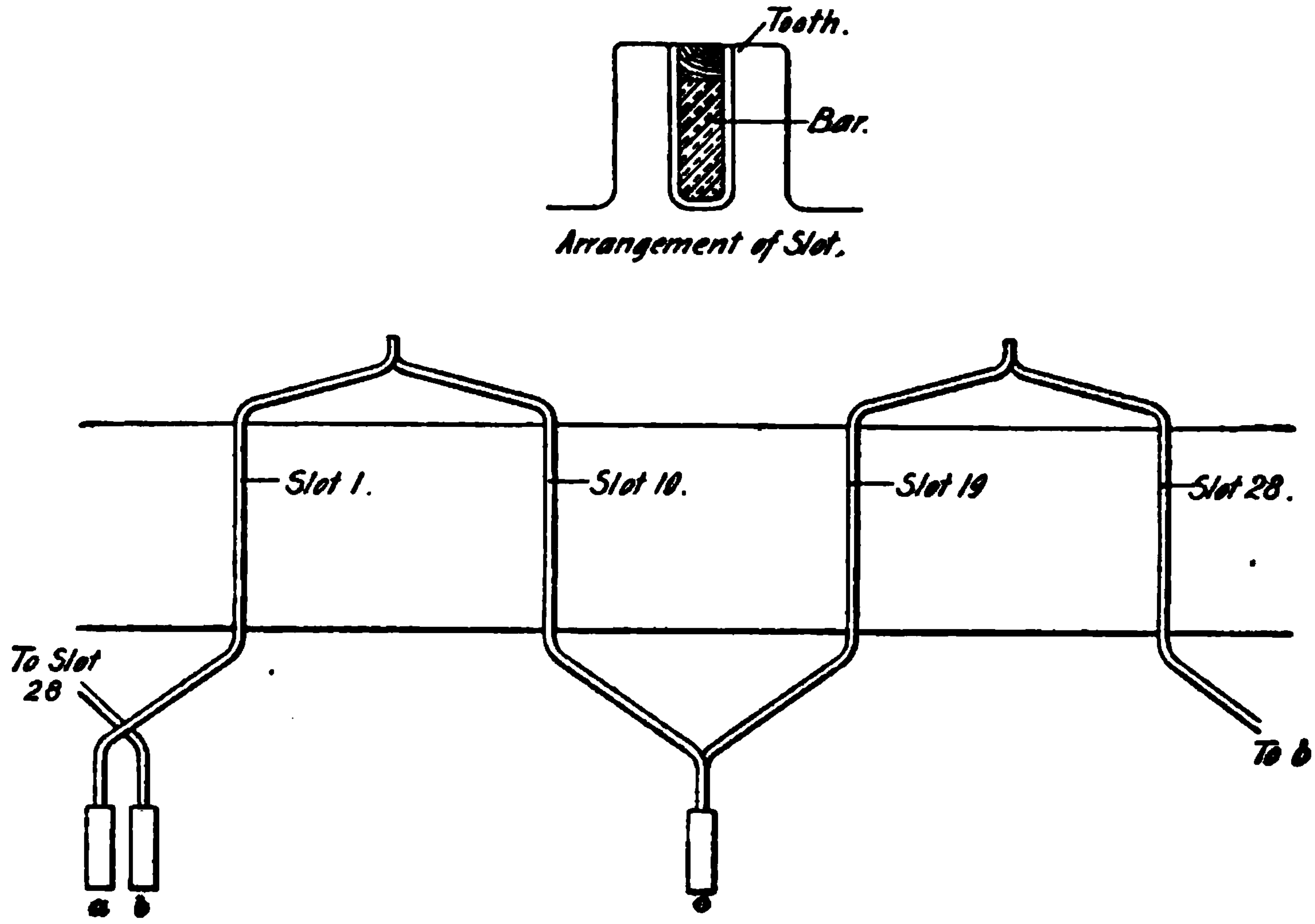
This includes all coils but *1–10*, which at the instant shown is short-circuited.



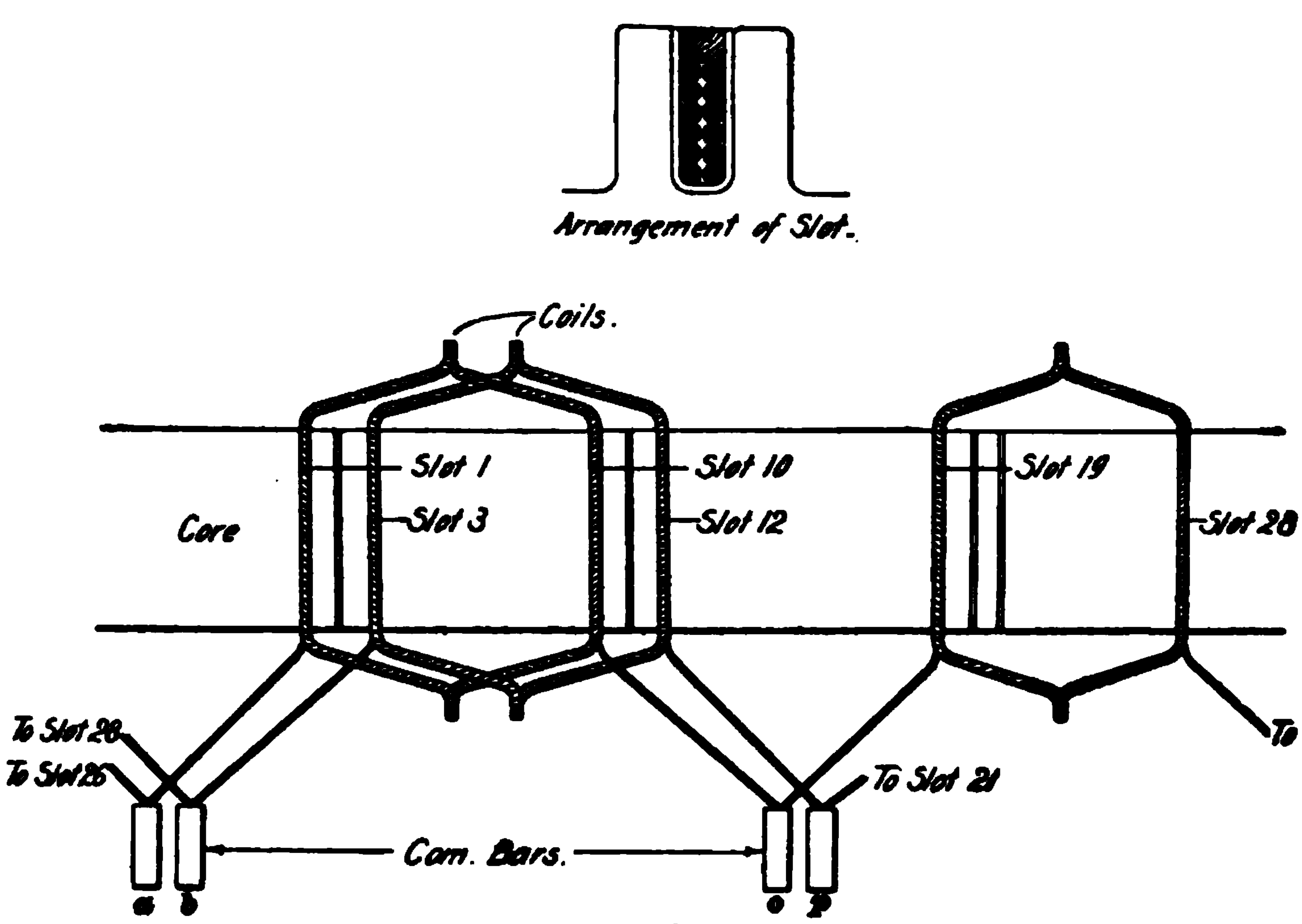
(a)

FI(


N
a


Teeth.
Bar.
Arrangement of Slot.
Slot 1.
Slot 10.
Slot 19
Slot 28.
To Slot 28
To b
a
b

(a)


Arrangement of Slot.
Coils.
Slot 1
Slot 3
Slot 10
Slot 12
Slot 19
Slot 28
Core
To Slot 28
To Slot 26
To Slot 21
To b
Com. Bars.
a
b
c

(b)

5

SERIES-WINDINGS

14. A diagram of a single **series-winding** of the single-layer type is shown in Fig. 5. This winding is exactly like that of Fig. 3, except in regard to the connections to the commutator, and both are open to the same objection that being in a single layer the end connections will interfere if the barrel type of winding is used. In these two diagrams, comparing (*c*), it will be noticed that in Fig. 3 the winding of one coil laps over that preceding it, while in Fig. 5, the winding progresses in a series of zigzag lines or waves. The former winding is therefore sometimes called a **lap winding** and the latter a **wave winding,** but the terms parallel and series are to be preferred, since they are applicable to both ring and drum types of windings, while the terms lap and wave are only applicable to the drum type.

15. The paths through the winding, Fig. 5, are as follows:

$$- \left\{ \begin{matrix} A, 1\text{–}10, 19\text{–}28, 3\text{–}12, 21\text{–}30, 5\text{–}14, 23\text{–}32, 7\text{–}16, 25\text{–}34, B \\ A, 26\text{–}17, 8\text{–}33, 24\text{–}15, 6\text{–}31, 22\text{–}13, 4\text{–}29, 20\text{–}11, B \end{matrix} \right\} +$$

At the instant shown, there are eight coils in one path and seven in the other, there being a series of two coils *9–18* and *27–2* short-circuited by the brush *B*. Since there are seven coils in one path and eight in the other, it would appear that the winding is not symmetrical and one path would take more current than the other, but turn the armature a small fraction of a revolution, and it will be found that the path that now has eight coils may then have seven and that with seven may then have eight, so that the two paths will have the same average number of coils, even though they may not be alike at a given instant. In actual windings, there are usually from twenty to fifty or more coils per path, and the differences caused by having one coil more or less in a path where the number is so great is insignificant.

16. Comparing the number of coils in series in each path of the windings, Figs. 3 and 5, shows that the latter

has twice as many as the former and, if the coils are the same in both cases and only the commutator leads changed, the latter will give twice the voltage of the former with but half of the current capacity, since it has but half the paths. The watts output of the winding remains unchanged, however, since doubling the number of volts and halving the current will give the same number of watts.

With the series-windings, but a single pair of brushes is required to collect the current, as shown, but the other neutral points may be also supplied with them, as shown by the dotted lines.

17. The winding fulfils the formula that the number of coils

$$C = \frac{p}{2} Y \pm 1 = \frac{4}{2} \times 9 - 1 = 17,$$

nine being the span of the coils on the commutator segments, that is, from *a* to *o*; the terminals of coil *1–10* are nine segments removed from one another. It will be seen that this same number of coils can be made into another winding with a pitch of eight, thus,

$$C = \frac{p}{2} Y \pm 1 = \frac{4}{2} \times 8 + 1 = 17$$

This winding is shown in diagram in Fig. 6, which is made after the two-layer type. Figs. 5 and 6 are electrically the same, except that in the former a series of $\frac{p}{2}$ coils spanned a circumference plus one segment on the commutator, while in the latter the series lacks one segment of spanning a circumference. The effect of this is to interchange the connections of the series of coils, so that the brushes exchange signs, although the direction of current in the face conductors is as before. It has the same effect as though the terminals of each coil were reversed at the commutator, as was explained for the parallel type of winding. To actually reverse the leads of each coil of the series-type of winding would require such extra-long leads that it would be impracticable.

18. Where drum-armature windings consist of but a single turn per coil, and often where there are many turns per coil, an inspection of the armature will usually show whether it is of the parallel or series-type in the following way: Consider face conductor *1*, Fig. 4, which is of the parallel type, and note that the end connections extend on both front and rear to the right. The same is true of conductors *3*, *5*, *7*, etc., as well as the even-numbered conductors, which, shown dotted, are underneath and are not visible on the completed armature. Referring to Fig. 6, it will be seen that the end connections on the rear end extend to the right from conductor *1*, while on the front end they extend to the left. It follows that if the end connections from a face conductor extend the same way on both ends, the armature winding is of the parallel type; while, if the end connections do not extend the same way, the winding is of the series-type. Whether the winding is single or double cannot usually be determined from the completed armature, except by testing the resistance between segments.

It will also be noticed that in Figs. 4 and 6 the coils span four slots on the armature, that is to say, coil *1–10* lies in slots *1* and *5*. With seventeen slots and four poles, four and one-quarter slots is the exact pole pitch and four is the nearest whole number.

19. Double Parallel Winding.—A **double parallel winding** could be readily made with seventeen coils and four poles by connecting coil *1–10* to segments *a* and *c*, coil *3–12* to segments *b* and *d*, etc., but such a diagram is not very instructive, for the brushes must be made thick enough to span about one and one-half segments at least, and with so few segments in the commutator, there would be but two coils in series per path, which does not approach practical requirements at all. However, the double parallel winding is so simple that it should be understood from what has been said, without the aid of a special diagram.

20. Double Series-Winding.—A **double series-winding,** however, cannot be made from seventeen coils and four

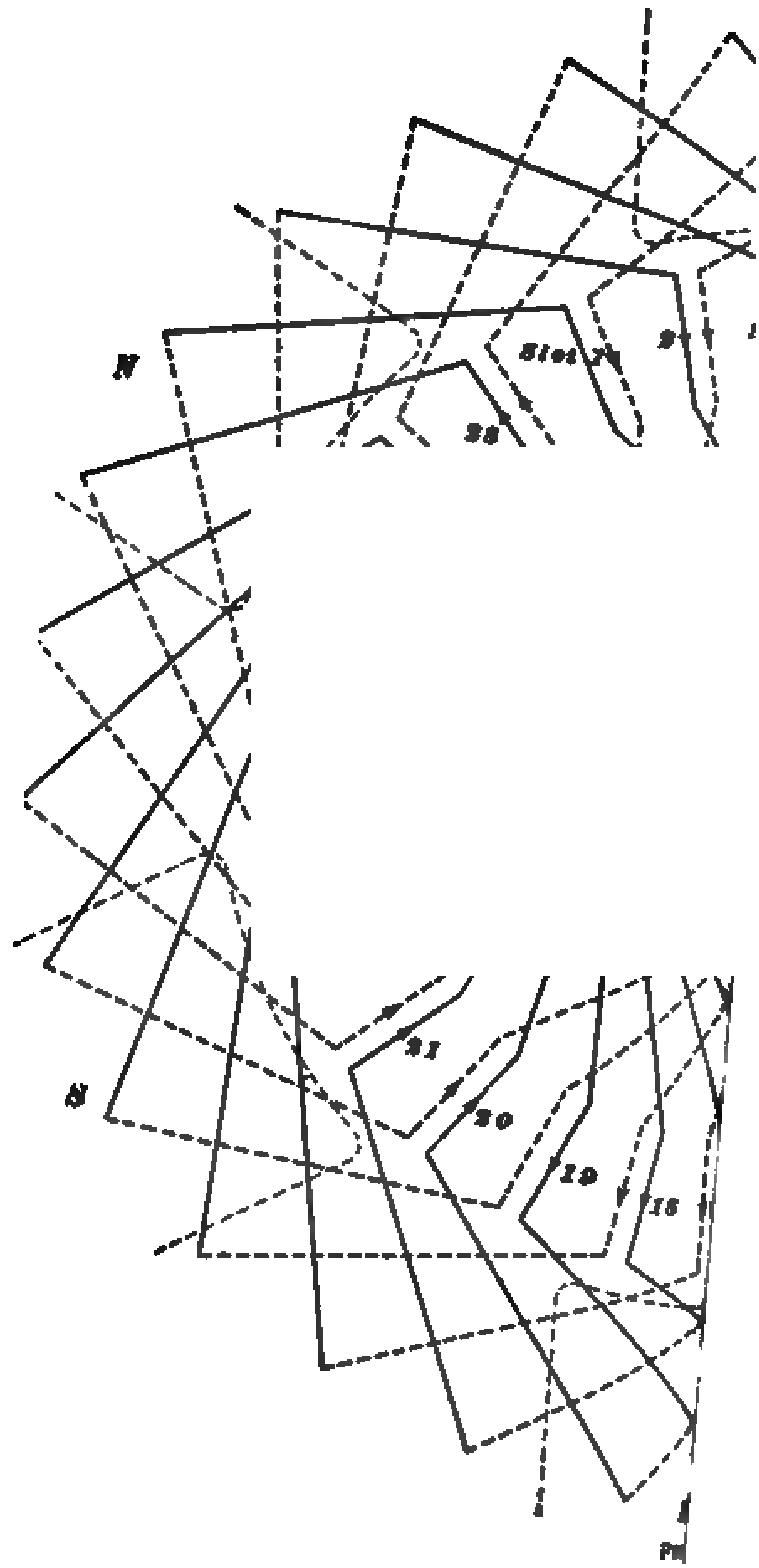
poles, because the number of coils must fulfil the formula, $C = \frac{p}{2} Y \pm 2$; and since $\frac{p}{2}$ in this case is even, C should be even regardless of whether Y is even or odd. Just why seventeen coils will not answer is seen by remembering that in a double series-winding, a series of $\frac{p}{2}$ coils should encircle the commutator with two segments over or less, or in this case two coils should span either fifteen or nineteen segments. All coils must be alike, so since fifteen and nineteen are not divisible by two, the winding is impossible.

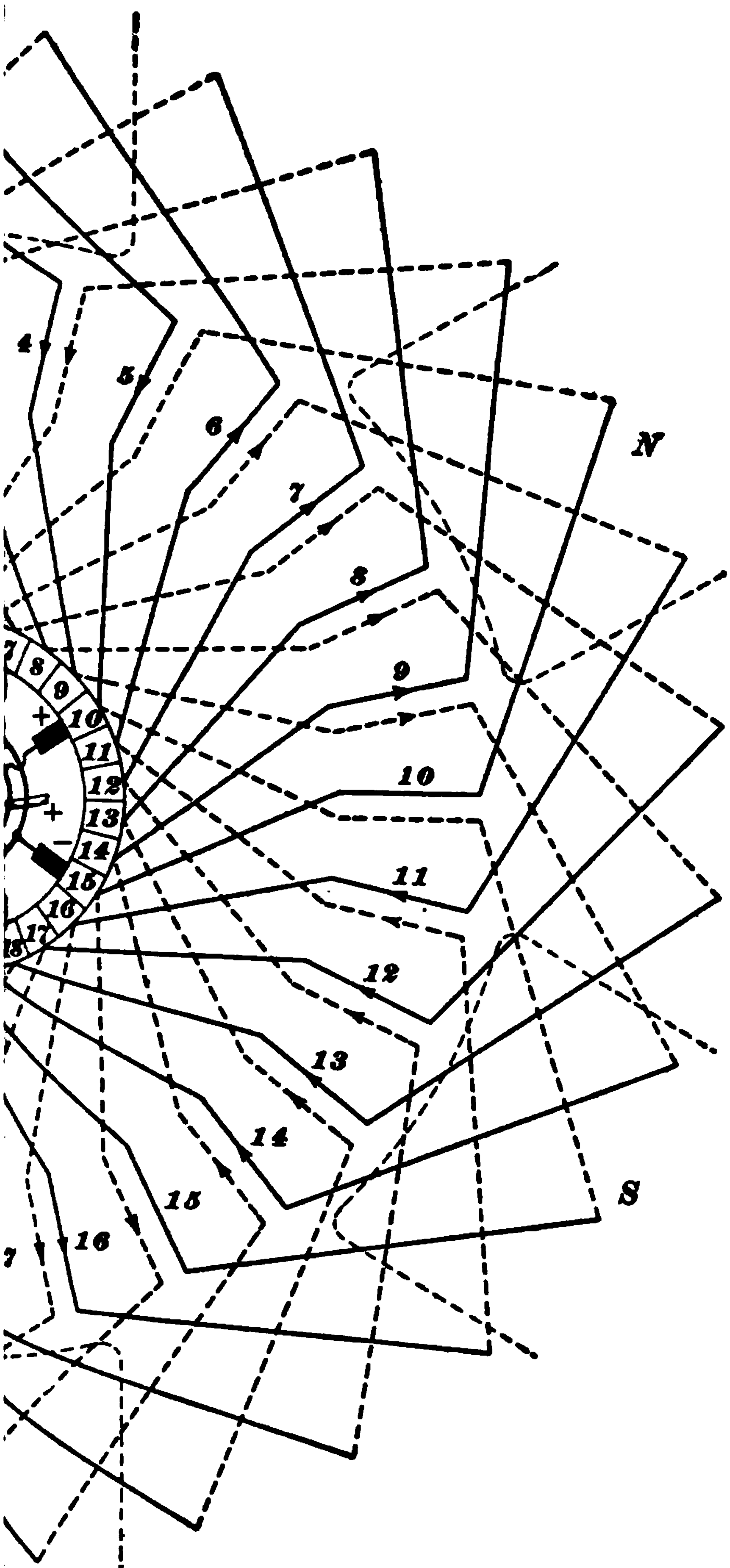
In Fig. 7 is shown a double series-winding for a six-pole armature with twenty-eight segments and coils and twenty-eight slots. The number of coils in this winding fulfils the formula $C = \frac{p}{2} Y \pm 2 = \frac{6}{2} \times 10 - 2 = 28$, and since the pitch Y is divisible by two, the winding is doubly reentrant. The four paths are as follows, the numbers referring to the commutator segments to which the coils are attached:

$$- \left\{ \begin{array}{l} 6\text{–}16,\ 16\text{–}26,\ 26\text{–}8,\ 8\text{–}18,\ 18\text{–}28,\ 28\text{–}10 \\ 5\text{–}23,\ 23\text{–}13,\ 13\text{–}3,\ 3\text{–}21,\ 21\text{–}11,\ 11\text{–}1 \\ 15\text{–}25,\ 25\text{–}7,\ 7\text{–}17,\ 17\text{–}27,\ 27\text{–}9,\ 9\text{–}19 \\ 24\text{–}14,\ 14\text{–}4,\ 4\text{–}22,\ 22\text{–}12,\ 12\text{–}2,\ 2\text{–}20 \end{array} \right\} +$$

Coils *6–24*, *1–19*, *5–15*, and *10–20* are short-circuited by brushes at the instant shown and are not active. It will be noticed that coils are not short-circuited by a single brush, as in the case of parallel windings, but are short-circuited by two brushes and the connections between brushes of like sign. The coils lie in slots *1* and *6*, *2* and *7*, etc., hence, the span of the coils on the armature is five slots, which is the nearest number to twenty-eight divided by six, the number of poles.

21. Bucking.—Many different windings have been proposed and used successfully, but the majority of armatures are wound with either the single parallel ring winding, the single parallel drum winding, or the single series-drum winding. The single parallel drum is by far the most


N
S
Slot 1
28
21
20
19
18


N
S
4
5
6
7
8
9
10
11
12
13
14
15
16
17
+
−

popular. For machines with six or more poles, with this winding, it becomes difficult to get the currents in the various paths to divide properly, especially if the poles for any cause should become of unequal strength. Suppose, for example, that the armature, through wear of the bearings, approaches appreciably closer to one pole than to the others. Since the air gap at this pole is less than the others, with the same magnetizing coils, this pole will become stronger, and the pole opposite it weaker; hence, the armature will be drawn towards the stronger pole by the unbalanced magnetic pull, which therefore tends to make the difficulty worse. Now, the conductors on one side of the armature will be in a stronger field and will therefore develop a greater E. M. F. than those on the other side, and the path that develops the greatest E. M. F. tends to take the greatest share of the current. If the E. M. F.'s developed by the various paths are very different, so that the E. M. F. of one path may overpower that of some other, heavy local currents will be developed within the armature. These are usually accompanied by trembling and groaning of the machine, due to excessive mechanical strains, and more or less violent sparking or flashing at the brushes. This phenomenon is called **bucking.** On account of the effects of armature reactions, it is somewhat more liable to occur in motors than in generators.

22. Cross-Connection of Armatures.—To prevent bucking, and to equalize the division of the currents in parallel-wound armatures, they are often **cross-connected.** It has been stated that points on the commutator that are two poles apart always remain at the same potential as the armature revolves. By cross-connection is meant the permanent connecting of points in the windings that always remain at the same potential. This is done by means of copper rings, Fig. 8 (*b*), which are connected to the winding at intervals exactly two poles apart. In the figure, the rings, seven in number, are attached to the rear end, and the leads *S*, *S* from the winding can be plainly seen. Each ring, it will be noticed, is connected to seven points in the winding;

(a)

FIG. 6

(b)

hence, the armature is intended for a field magnet with seven pairs of poles, or fourteen poles. The armature shows the method of construction followed by the General Electric Company. Many other builders put the cross-connecting rings beneath the winding on the commutator end, making the connections to the commutator segments in the same manner as for the coils. In order that a winding shall properly cross-connect, it is necessary that there be a whole number of segments for every two poles; or, in other words, the number of segments should be divisible by the number of pairs of poles. In Fig. 8 (*a*), the armature bars are seen at ***a***, ***a***; ***b***, ***b*** are the leads connecting to the commutator *A*.

Double windings, both parallel and series, are not very reliable, and are but little used. They are more liable to sparking than are single windings, and if the commutator becomes in the least irregular, a segment higher than its neighbor will raise the brushes and open the circuit to the winding with the lower segment. A destructive spark results, and the low segment will be burned lower, thus aggravating the trouble.

OPEN-COIL ARMATURE WINDINGS

23. In Figs. 7 and 10 of Part 1, are shown typical **open-coil armatures,** one with the drum type and the other with the ring type of coils. It will be observed from the manner of connecting these coils to the commutator that they do not form closed circuits, for in them only one terminal, or lead, of a coil connects to a commutator segment; hence the name *open-coil.* These windings are now used commercially in America on three types of dynamos. The Brush and T-H arc dynamos, made by the General Electric Company, and the Westinghouse arc dynamo, all of which are constant-current machines; that is, they are machines that are provided with some means of regulating the current so as to keep it at some fixed value, usually either 6.8 or 9.6 amperes. They are all used for series-arc lighting, the arc lamps having been found to operate well at the currents given.

24. Consider the action of the armature shown in Fig. 10 of Part 1; the current entering by the negative brush finds but a single path to the positive through one of the sets of coils, and as the armature rotates, the brushes slide from one pair of segments to the other, and the inactive coil now becomes active, carrying the whole current, and so on. Since there is only one set of coils active at once, it is evident that for economy such armatures should not have many coils, as their period of activity would be shortened. With brushes and commutator as shown, the current of the machine will be very suddenly shifted from one path to the other, and this will cause serious sparking on account of the self-induced E. M. F. of the coil. A conductor carrying current tends to surround itself with a magnetic field, and a coil, especially one surrounding iron, will become a powerful magnet, as has already been explained. If this current is varied, the magnetic field must change in proportion; and if reversed, the field must also be reversed. The changing of the number of magnetic lines of force through a loop or coil is the same in effect as the cutting of lines of force with its conductors, and induces an E. M. F. in the coil independently of any cutting of the magnetic field emanating from the poles. Thus, the E. M. F. of self-induction is proportional to the rate of change of self-induced magnetism; or since this varies directly with the current, it is proportional to the rate of change of current. The direction of this self-induced E. M. F. is such as to tend to prevent the increase of current and to tend to maintain it after the current has been established; it causes the currents to act as though the electricity has weight and is often compared to inertia for purposes of illustration. In the case of the armature in question, the sudden shifting from one path to the other will induce high E. M. F.'s in the coils, because of the great rate of change of current, which tends to maintain the current in the coil just being cut out of circuit and to prevent the increase of current in the coil just brought into circuit, both of which would cause the current to spark or leap through the air from the brush to the segment that has just

left it. This spark, or arc, although perhaps small, is very hot and vaporizes, or melts, the brushes and segments and should be prevented if possible.

25. A less rapid rate of change of current can be obtained by making the commutator segments overlap, after the

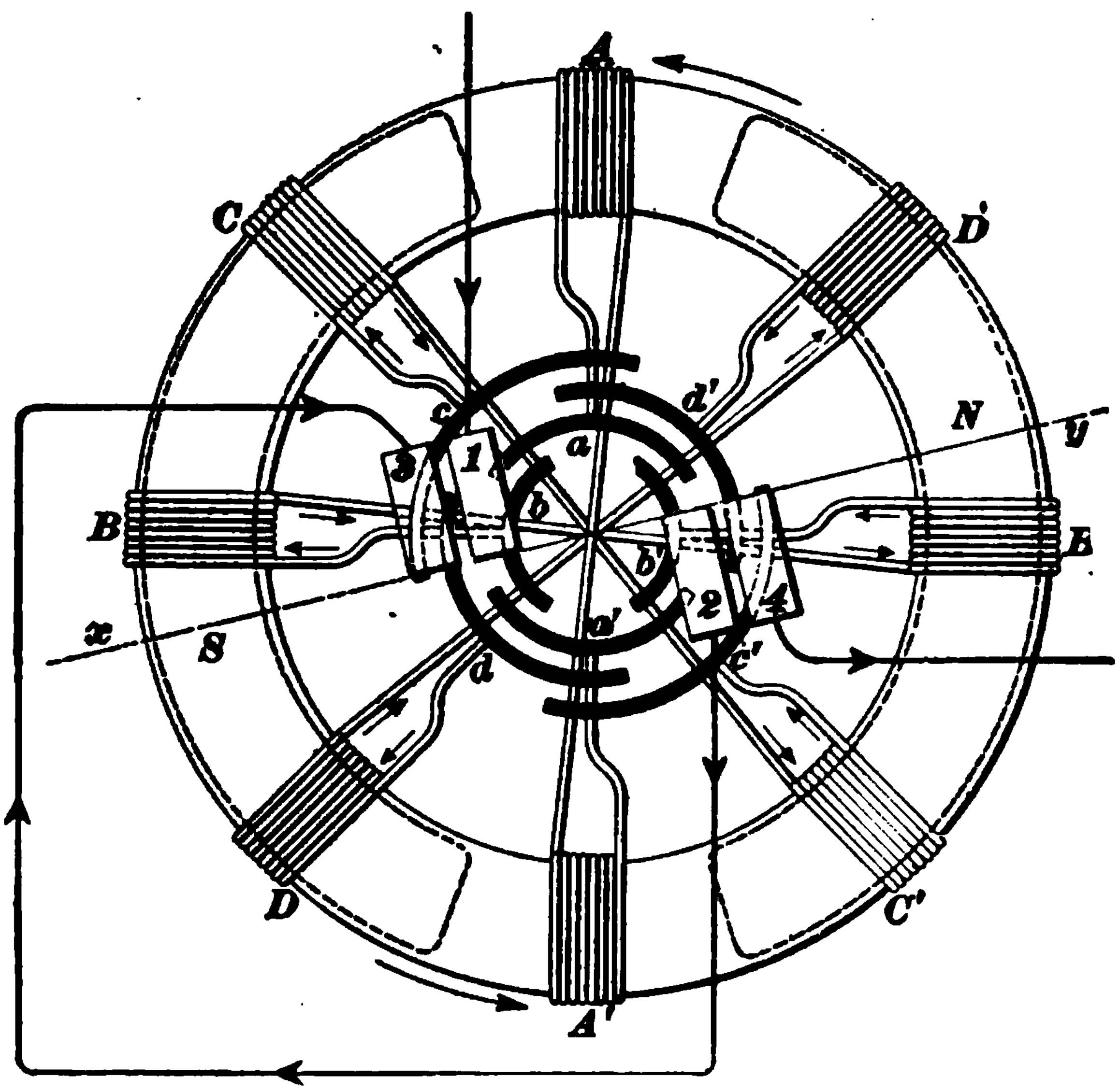


FIG. 9

manner of Fig. 9, or by using very thick brushes or their equivalent, two brushes in parallel, as shown in Fig. 10. This connects the coils in parallel for an instant, as the armature rotates, and the brushes are so placed that during this interval the coil coming into action has a greater E. M. F. than that going out, while the latter is overpowered and its current stopped by opposing the self-induced E. M. F. by the difference between

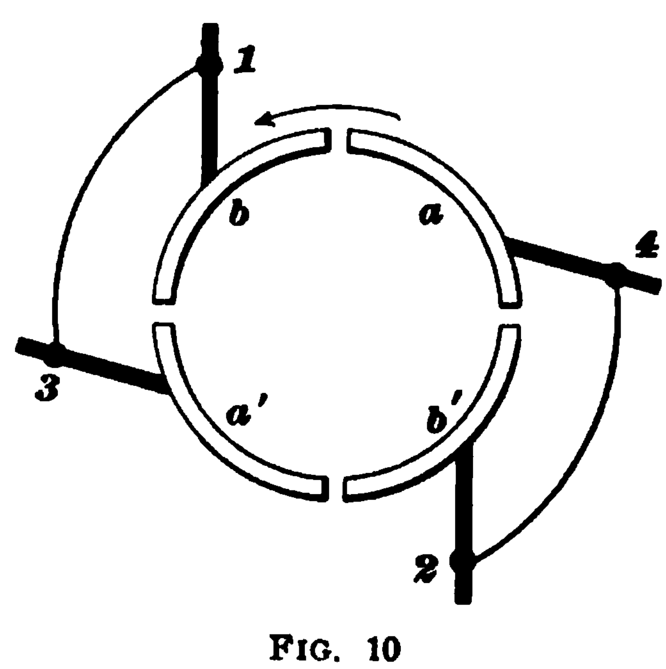


FIG. 10

the E. M. F.'s of two coils connected in parallel. The duration of the parallel connection must exist long enough to permit the current to die out, but not long enough to allow it to build up in the reverse direction, or sparking would again ensue.

26. Brush Constant-Current Dynamo.—Fig. 9 is a diagram of a two-pole Brush armature with two commutators connected in series, each of which is connected to windings exactly like Fig. 10 of Part 1. In this figure, the pole pieces are represented by the dotted lines as they face the sides of the armature. The segments of the two separate commutators are, for convenience, represented as concentric, with the brushes resting on their edges; whereas, actually, they lie side by side, forming two separate commutators of the same diameter, each having four segments, and the brushes rest on their circumferences, as shown in Fig. 11.

FIG. 11

One winding consists of two pairs of coils *A A'* and *B B'* located at right angles to each other, the coils of each pair being connected in series, as represented. This winding is connected to its commutator, coil *A* to segment *a*, coil *A'* to segment *a'*, coil *B* to segment *b*, and coil *B'* to segment *b'*, as represented. Brushes *1* and *2* rest on this commutator, making contact on the line *x y* of maximum action of the coils. It will be seen that this line is not from center to center of the pole pieces, but is moved ahead (in the direction of rotation, as indicated by the arrows) from this position by the armature reaction.

The second winding consists of two pairs of coils *C C'* and *D D'*, located at right angles to each other and half way between the coils of the first winding. These coils are connected in series and to the segments of the second commutator, coil *C* to segment *c*, coil *C'* to segment *c'*, coil *D* to

segment *d*, and coil *D'* to segment *d'*, as represented. Brushes *3* and *4* rest on the segments of this commutator on the same line of maximum action of the coils.

Taking each winding separately, it will be seen that its two sets of coils pass through the following combinations: One set of coils only connected to the brushes; then the two sets, connected in parallel and both connected to the brushes; then one set only; then both sets in parallel; and so on.

The maximum E. M. F. occurs when the single set of coils is connected and is directly in the line of maximum action; the minimum occurs one-eighth of a revolution ahead of this point, when both sets of coils are in parallel and are equally distant from the line of maximum action.

This being the case, it is evident that as the coils of one winding are half way between the coils of the other, the maximum E. M. F. of one winding occurs at the same instant as does the minimum E. M. F. of the other. On account of this, when the two windings are connected in series, the fluctuations of the current are much reduced. This connection of the two windings is obtained by connecting, as shown in Fig. 9, the positive brush of one winding with the negative of the other, the external circuit being connected between the two remaining brushes.

In the large sizes of these machines, three, and even four, separate windings are used, each with its commutator, and all connected in series. In the larger multipolar machines, each winding consists of two sets of coils, each set containing four coils, one for each pole piece. The action is precisely the same as in the bipolar machine.

27. Thomson-Houston Constant-Current Dynamo. Referring again to Fig. 10 of Part 1, it has been found that the action of the machine is the same if the two coils are connected together at the point where they cross each other, shown by the heavy black dot in Fig. 12, as these points in the two coils always remain at the same potential; the resulting winding is shown diagrammatically in Fig. 12, which may be considered as having four coils instead of two.

If one of these coils is omitted, the diagram will be that of the Thomson-Houston arc dynamo, in which there are but three coils—one end of each being connected together, the other ends to each of three segments. These segments are insulated from one another by an air space of about 10° opening, so the segments themselves span about 110° each.

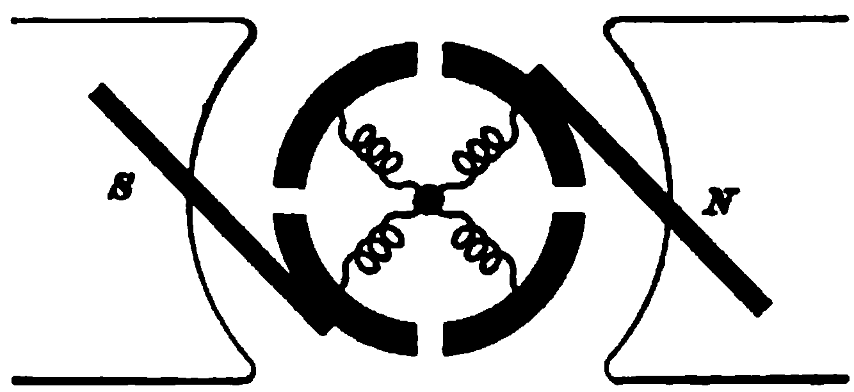


FIG. 12

Two sets of brushes are used, as in Fig. 10, whose positions are automatically controlled by a regulating magnet to maintain the current constant regardless of the voltage. This regulating magnet is mounted on the frame of the

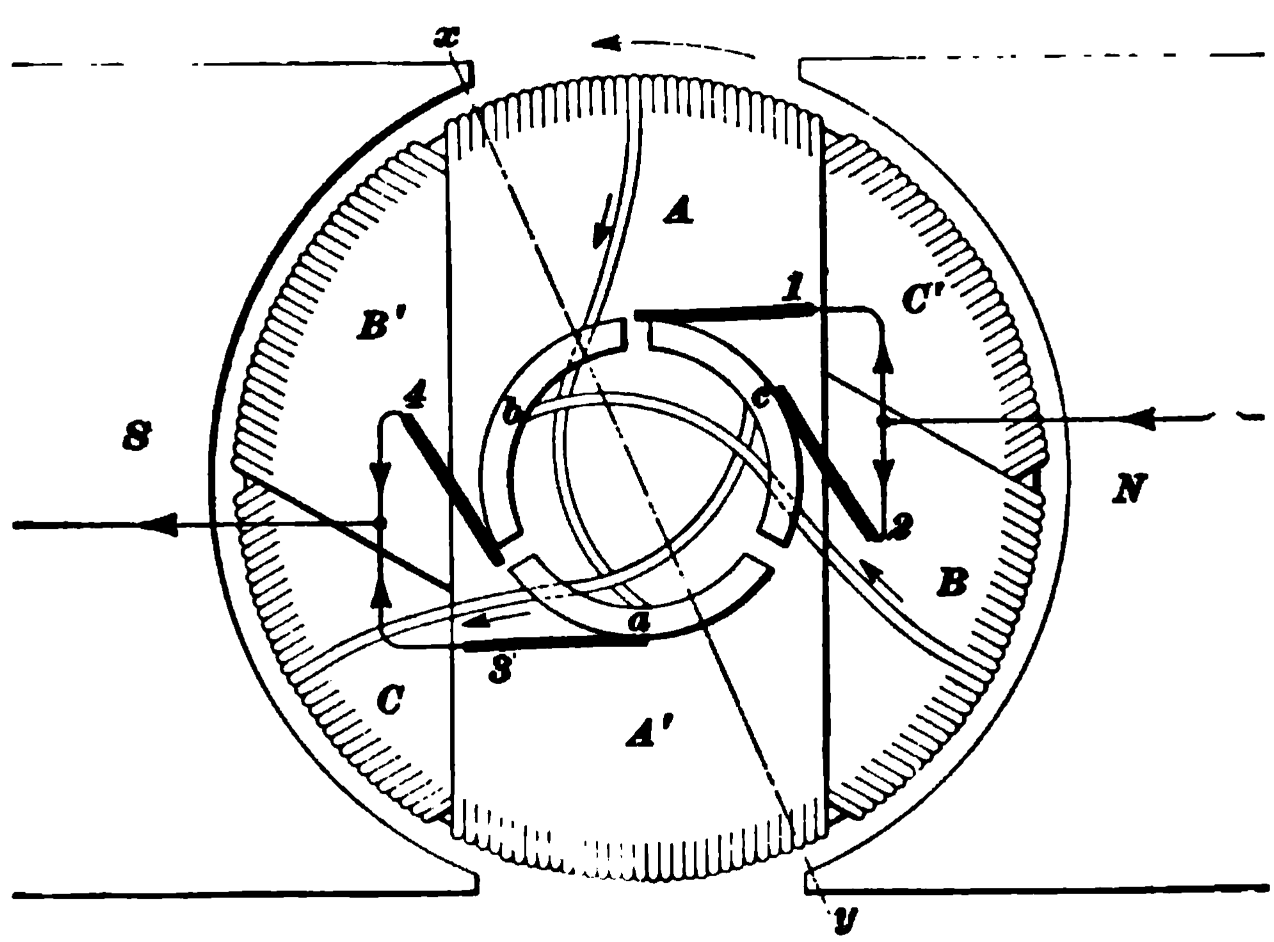


FIG. 13

machine, and the current flowing through it is controlled by means of a wall controller, through which the current from the machine passes. These machines have been largely used for arc lighting and are still found in many of the older stations. Under full load, that is, maximum voltage, the brushes of like sign are about 60° apart, as shown in Fig. 13, while under no load, outside circuit short-circuited,

brushes *1* and *3* are moved forwards (in the direction of rotation) 10° and brushes *2* and *4* backwards 20°, so that those of like sign are about 90° apart.

In the older machines, the armature is drum-wound, although the core is a ring, but in the newer machines a ring winding is used; in either case, three separate coils, or sets of coils, make up the winding.

28. A diagram of the connections, etc. of the drum-wound armature is shown in Fig. 13. $A A'$, $B B'$, and $C C'$ are the three coils wound on the core one-third the circumference apart. One end of each of the coils is joined to a metal ring (not represented in the figure) on the back of the armature, which forms a common connection for the three. The other ends are joined to the commutator segments, that of $A A'$ to segment *a*, that of $B B'$ to segment *b*, and that of $C C'$ to segment *c*, as represented; *1* and *2* are the negative, and *3* and *4* the positive, brushes. Brushes *2* and *4* are usually called the *primary brushes* and *1* and *3* the *secondary brushes*, to distinguish them.

29. From the diagram, Fig. 13, it will be seen that coil $A A'$, though half way between the pole pieces, is partly active, since the neutral line is shifted forwards, in a manner that will be taken up later, into the position indicated by the line *x y*. This coil $A A'$ is connected in parallel with the coil $B B'$ by the two positive brushes, and the two are in series with coil $C C'$. If the armature be considered as moving in the direction indicated by the arrow, it will be seen that as coil $A A'$ gets to the position of least action, it is disconnected from the circuit by segment *a* passing out from under brush *3*, leaving coil $B B'$ and coil $C C'$ in series. However, as the distance between brush *3* and brush *2* is only slightly greater than the span of one segment, coil $A A'$ is almost immediately connected in parallel with coil $C C'$, as segment *a* passes under brush *2*, making the following combination: Coil $B B'$ in series with coils $A A'$ and $C C'$ in parallel.

As the rotation of the armature continues, coil $C C'$ is disconnected from the negative brush *1* and connected to the positive brush *4*, being thus thrown in parallel with coil $B B'$, the two being then in series with coil $A A'$. Completing the half revolution, coil $B B'$ is disconnected from the positive brush *3* and is joined in parallel with coil $A A$ by the two negative brushes *1* and *2*, leaving coil $C C'$ connected to the positive brushes. Further rotation of the armature repeats this series of connections; that is, during every half revolution, one of the coils ($A A'$ in the preceding paragraphs) is first in parallel with the coil behind it, then momentarily disconnected from the circuit, then connected in parallel with the coil ahead of it, then connected in series with the other two, which are then in parallel.

30. From Fig. 13, it will be seen that when a coil is disconnected from one set of brushes it is very nearly in the position of least action, and the coil with which it was just before connected in parallel has the higher E. M. F. of the two. As explained, the self-induction of the coil prevents the higher E. M. F. of the other sending a current through it in opposition to its own E. M. F. at the time when they are connected in parallel; in fact, when a coil is disconnected from its mate it is still supplying some of the current, so that there is a spark at the brushes.

There being but three sets of coils in this machine, a great number of turns must be used in each coil to give the required E. M. F., which gives each set of coils a high inductance. This lessens to a great extent the fluctuations in the E. M. F. acting on the external circuit, which would otherwise be very considerable, owing to the small number of coils used and the changes in the manner in which they are interconnected.

In the full-load position, only a small fraction of a revolution (about 10°) is required to carry a segment from contact with one set of brushes to contact with the other, but if the arc of contact is increased to 70°, or more, the armature

will be short-circuited by brushes of opposite sign touching the same segment. This short-circuiting occurs at two places, i. e., between brushes *1* and *4*, and *2* and *3*, and, there being three commutator segments, six short-circuits occur during a revolution. It will be seen that this short-circuiting does not reduce the maximum value of the E. M. F., but as it introduces periods in each revolution where the E. M. F. between brushes is zero, it does reduce its effective value. By varying the arc of contact, and thus varying the length of time of the short circuit, the effective E. M. F. of the machine may be varied between quite wide limits. As the field magnets are in series with the armature, their great self-induction prevents the strength of the current falling to zero, and its fluctuations are therefore comparatively small. At the same time, the self-induction of the armature coils prevents any excessive flow of current in them during a short circuit.

31. Thus far, the open-coil winding has only been considered with reference to bipolar fields. It is evident, however, that introducing multipolar fields will only result in a duplication of the parts used with a bipolar field for each pair of poles of the multipolar field. Thus, for a winding for a four-pole field equivalent to that shown in Fig. 10 of Part 1, four coils would be required in each set.

Since each set would have to go through its various combinations of connections during each half revolution, instead of each revolution, it is evident that twice as many commutator segments, of one-half the span, would be required, or, rather, each segment would be divided into two. These two parts of the segment would be situated directly opposite each other, and either four brushes would be used on each commutator, of which the opposite brushes would have to be connected together, or the opposite commutator segments would be permanently connected together, and only two brushes would be used. This latter plan is best, as permanent connections are less difficult to maintain than sliding connections.

UNIPOLAR DYNAMOS

32. Unipolar Induction.—In all the armatures so far considered, the conductors as they revolve pass successively under poles of opposite polarity. The E. M. F. set up in a given conductor, or group of conductors, is alternating because the conductors at one instant move under a north pole and a moment later they pass under a south pole. If arranged so that the armature conductors will always cut across the field in the same direction, the E. M. F. and current resulting therefrom will always be in the same direction and no commutator will be necessary to secure a direct current. Such a machine is commonly known as a **unipolar dynamo**; the term **homopolar** has also been suggested as more appropriate because it is impossible to construct a dynamo with only one pole. Unipolar dynamos have never been used in practical work except for a few special purposes, where a very large current at low voltage is desired. However, on account of the introduction of the steam turbine for driving dynamos, it is possible that unipolar machines may be used more in the future and the principles involved in their operation will, therefore, be taken up briefly.

33. If a copper disk is mounted, so that it projects between the poles of a horseshoe magnet, and then rotated, the lines of force passing through the disk from pole to pole will be cut, and an E. M. F. will be generated. If one connection is made to the shaft and another to the periphery of the disk, by means of a sliding contact, an E. M. F. will be obtained between the two terminals. The disk is equivalent, electrically, to a large number of radial conductors connected in parallel, and the E. M. F. generated is the same as that obtained from a single conductor only; however, on account of the low resistance of the disk or

armature, the machine can furnish a very large current. The lines of force are always cut in the same direction, hence the E. M. F. induced is direct and absolutely continuous.

34. In order to obtain any considerable E. M. F., it is necessary to use either a very large disk and magnet or to rotate the disk at an exceedingly high speed. Many attempts have been made to build unipolar machines in which a number of disks, or conductors, would be connected in series, so as to produce the E. M. F. desired; but all these proved failures because the magnetic lines always form closed loops, and it is impossible to connect conductors in series without the connections themselves also cutting the lines in an opposite manner, thus producing an E. M F. that exactly neutralizes that which would otherwise be obtained by the series-connection. It is possible, however, to obtain a high E. M. F. by connecting two or more of the revolving disks, or conductors, in series by means of sliding contacts, thus making the connecting wires stationary and preventing the generation of opposing E. M. F.'s. Heretofore, the E. M. F. that it has been possible to generate per conductor has been comparatively small and in order to get pressures such as 110, 220, or 500 volts, a large number of sliding contacts would be required, thus making the machine fully as complicated as an ordinary dynamo with a commutator.

The development of the steam turbine, however, affords a simple means of procuring high rotative speeds and the number of disks can be reduced, so as to make the machines practicable in this respect, but there remains the difficulty of getting sliding contacts that will operate well at the high peripheral speeds of the disks for turbine-driven machines. It is difficult to design ordinary direct-current dynamos for direct connection to steam turbines, because the high rotative speed makes it hard to secure sparkless commutation in machines of large output. Unipolar machines are free from this trouble because there is no commutator.

35. Fig. 14 shows the essential parts of two unipolar machines of the disk type. In (*a*), a single copper disk *a* is rotated in a magnetic field set up across the air gap of the annular magnet *b* by means of coil *c*; the path of the magnetic flux is indicated by the dotted lines. In (*b*), two

(*b*)

FIG. 14

disks and two magnets are used and the magnetizing coils are connected so that the field passes through one disk in a direction opposite to that through the other. The disks being in series through the shaft, the E. M. F. between terminals *d* and *e* will be twice as great for machine (*a*) as for (*b*), assuming the speed, dimensions, etc. to be the same in both cases. In both machines, current is collected by a number of sliding contacts projecting through the field frame and bearing against the sides of the disks near the periphery, as indicated at *f*. Unipolar machines have been built in which the armature is in the form of a drum or cylinder, but for high-speed machines connected to turbines, the disk form is preferable because it can be made of more homogeneous material and more accurately balanced. A unipolar machine of the type shown in Fig. 14 would have a very low armature

resistance because of the large cross-section of the disks. The size of the machine as a whole is determined nearly altogether by the voltage to be generated, because the disks must have a certain cross-section in order to secure mechanical strength, and the cross-section thus determined will usually have sufficient current-carrying capacity. For these reasons, also, unipolar machines cannot be built advantageously for small output. In the machines shown in Fig. 14, the disks are of copper, but in large dynamos, where heavier disks must necessarily be used, the thickness would become so great as to insert a large air gap in the magnetic circuit, and steel disks are preferable. Where two disks, as in Fig. 14 (*b*), are connected in series, an E. M. F. of 50 volts could be generated with disks about 32 inches in diameter run at a speed of 2,500 revolutions per minute, assuming that the magnetizing coils set up a density of 95,000 lines per square inch in the air gap in which the disk rotates.

CALCULATION OF E. M. F. AND POWER

36. Calculation of E. M. F.—The fundamental principle on which all E. M. F. calculations are based is that a conductor moving across a magnetic field at a rate such that a hundred million, or 10^8, lines are cut per second, has an E. M. F. of 1 volt induced in it. This can be reduced to handy working equations for any type of windings. For direct-current closed-coil windings the E. M. F. formula may be derived as follows:

Let p be the number of poles of the field magnet; Φ, the total number of lines of force entering or leaving the armature at each pole piece; S, the number of revolutions per minute of the armature; Z, the number of face conductors on the armature; and m, the number of paths, or circuits, through the winding. Then, $p\,\Phi$ lines of force are cut by a single conductor in a revolution, or, in 1 second, each face conductor would cut $\frac{p\,\Phi\,S}{60}$ lines, so that the average voltage

developed by the conductor would be $\frac{p \Phi S}{60 \times 10^8}$. The voltage obtained at the brushes will be equal to the voltage per conductor multiplied by the number of conductors in series between the brushes. There are Z conductors on the armature arranged into a winding with m paths, and since the voltage of all paths must be alike, the windings must be such as to have as many conductors in series on one path as on another, or, at least, to have the number average the same on all paths. So the average number of conductors in series on each path will be $\frac{Z}{m}$, and as the voltage of the armature E is the same as that of one of the parallel paths, then

$$E = \frac{p \Phi S}{60 \times 10^8} \times \frac{Z}{m},$$

which may be written

$$E = \frac{p \Phi Z S}{m \times 10^8 \times 60}, \qquad \textbf{(1)}$$

which is the fundamental equation for E. M. F. For open-coil windings, the average number of face conductors in series should be substituted for $\frac{Z}{m}$.

Formula **1** is perfectly general for closed-coil windings of any kind with either drum-wound or ring-wound coils in a field with any number of poles.

37. Calculation of Power.—The number of watts output of an armature is numerically the product of the E. M. F. in volts and the current in amperes. This number is usually divided by a thousand for convenience, and the output expressed in kilowatts, abbreviated K. W. Let I be the total current in amperes, either entering or leaving the armature; this equals the sum of the currents in, say, all positive brushes, and let i be the current in amperes in each face conductor. Then, since the current divides into m paths

equally, $I = m\,i$. Now the total electrical power developed in the windings in watts is

$$W_t = E\,I = \frac{p\,\Phi\,Z\,S}{m \times 10^8 \times 60} \times m\,i$$

$$= \frac{p\,\Phi\,S}{10^8 \times 60} \times Z\,i \qquad (2)$$

$Z\,i$ is the product of the amperes in each conductor and the total number of face conductors, and may be called the *total armature ampere conductors*. $p\,\Phi$ is the product of the number of poles and the total magnetic flux from one pole, and is sometimes called the *total magnetic flux* of the machine. So it may be stated that

$$W_t = \frac{\text{total magnetic flux} \times \text{total ampere conductors} \times \text{R.P.M.}}{10^8 \times 60} \qquad (3)$$

The quantity $p\,\Phi$ may be expressed in terms of the dimensions of the armature and of the magnetic density in the air gap thus: Let $\mathbf{B}_g$ equal the average magnetic density in lines per square inch in the air gap between the poles and the armature core, and let $\%$ be the percentage of the cylindrical surface of the armature core covered by poles; this percentage is to be expressed as a decimal. Also, let D be the diameter of the armature core in inches, and L the length of the armature core in inches. Then, $\pi\,D\,L$ is the area of the cylindrical surface of the armature core, and $\%\,\pi\,D\,L$ is the area of the cylindrical surface of the core covered by poles; and since the magnetic density in this area is $\mathbf{B}_g$,

$$p\,\Phi = \%\,\pi\,D\,L\,\mathbf{B}_g$$

The total ampere-conductors $Z\,i$ in a given line of machines usually varies, approximately, with the diameter of the armature core, and may be conveniently expressed in ampere conductors per inch of diameter or per inch of circumference. Using the latter, let K be the ampere conductors per inch of circumference of the armature core, then,

$$Z\,i = \pi\,D\,K$$

Substituting the value of $p\,\Phi$ in formula **2**, gives

$$W_t = \frac{\%\,\pi\,D\,L\,\mathbf{B}_g \times Z\,i}{10^8} \times \frac{S}{60} \qquad \textbf{(4)}$$

and substituting in this the value of $Z\,i = \pi\,D\,K$ gives

$$W_t = \frac{\%\,\pi^2\,D^2\,L\,\mathbf{B}_g\,K}{10^8} \times \frac{S}{60} \qquad \textbf{(5)}$$

Thus, the watts output of any armature can be expressed in terms of the six quantities $\%$, D, L, $\mathbf{B}_g$, K, and S, along with the constants given. If five of these quantities are known, the sixth can be computed.

38. Considering formula **5**, it will be noticed that the watts are independent of the number of poles if the other quantities are constant; also the voltage, the number of paths, and the number of face conductors do not enter the equation. If the speed in revolutions per minute is fixed, the watts developed will vary with the square of the diameter of the armature; but if the peripheral velocity instead of the speed were limited, this would not be true.

39. Total Power and Available Output.—The watts expressed in formula **5** must not be taken as the output of the machine or even the output of the armature itself; they are the watts developed within the windings. A small portion of the E. M. F. is used in forcing the current through the armature resistance and commutator resistance, and if the field magnet has a series-winding, there will be a drop in volts in that also. If the field magnet has a shunt winding, the outside circuit will not receive all the current developed in the armature windings, as a part will be used in the shunt field coils. These losses are known as the **electrical losses,** since they occur only after the electrical energy has been developed; the **electrical efficiency** is the ratio of the electrical watts output to the electrical watts developed.

Let U_e = electrical efficiency of a dynamo,

W = watts supplied to the external circuit.

Then, $$U_e = \frac{W}{W_t} \text{ or } W_t = \frac{W}{U_e} \qquad (6)$$

If we call W_t the total power in watts supplied to the dynamo by the belt or engine, then the ratio of the watts developed W_t to the total watts W_t is called the **efficiency of conversion** U_c. W_t is less than W_t by the watts lost in bearing and commutator brush friction, by windage or air friction, by hysteresis and eddy currents in the armature core, and also by eddy currents in any solid masses of metal in which they may be developed. The total efficiency of the machine U is called the **commercial efficiency.**

$$U_c = \frac{W_t}{W_t} \qquad (7)$$

$$U = \frac{W}{W_t} = \frac{W_t \times U_e}{W_t} = \frac{W_t}{W_t} \times U_e = U_c \times U_e \qquad (8)$$

or the commercial efficiency equals the product of the electrical efficiency and the efficiency of conversion.

EXAMPLE 1.— 10 horsepower is supplied to the pulley of a dynamo and a total E. M. F. of 120 volts is generated in the armature. The armature delivers a current of 55 amperes. What is the efficiency of conversion of the dynamo?

SOLUTION.—The efficiency of conversion U_c is the ratio of the total watts developed in the armature to the total watts supplied to the machine; i. e., $U_c = \frac{W_t}{W_t}$, formula **7**. In this case, the number of watts supplied is, $W_t = 10 \times 746 = 7{,}460$. The number of watts developed is $120 \times 55 = 6{,}600$; hence the efficiency of conversion

$$U_c = \frac{W_t}{W_t} = \frac{6{,}600}{7{,}460} = .8847, \text{ or } 88.47 \text{ per cent. Ans.}$$

EXAMPLE 2.—In the above example, the loss in the field coils is 250 watts, and 4 volts is lost in the armature when a current of 55 amperes is delivered. What is the electrical efficiency of the dynamo?

SOLUTION.—If 4 volts is lost in the armature, the number of watts lost must be $55 \times 4 = 220$. Hence, the total watts electrical loss is $220 + 250 = 470$, and the watts W' delivered at the terminals of the machine will be $6{,}600 - 470 = 6{,}130$. The electrical efficiency is

$$U_e = \frac{W'}{W_t} = \frac{6{,}130}{6{,}600} = .9288, \text{ or } 92.88 \text{ per cent. Ans.}$$

EXAMPLE 3.—What is the commercial efficiency of the machine?

SOLUTION.—The commercial efficiency is

$$U = \frac{W}{W_t} = \frac{6,130}{7,460} = .8217, \text{ or } 82.17 \text{ per cent. Ans.}$$

This may also be found as follows. The commercial efficiency

$$U = U_c \times U_e = .8847 \times .9288 = .8217, \text{ or } 82.17 \text{ per cent. Ans.}$$

40. Conversion of Mechanical Into Electrical Energy.—That there is no loss in the actual conversion of mechanical into electrical energy may be shown as follows: Imagine the armature D inches in diameter and L inches long to have $\%$ of its surface covered by poles with a magnetic density of $\mathbf{B}_g$ lines per square inch, and let there be i amperes flowing in each of Z conductors, equally spaced around the armature. There are $\% \; Z$ conductors in the magnetic field of a strength of $\mathbf{B}_g$ lines per square inch with i amperes flowing in each.

The unit current strength has been defined as that current which, when passing through a circuit of 1 centimeter in length bent in an arc of 1 centimeter radius, will exert a force of 1 dyne on a unit magnet pole at the center, and this unit current is ten times as large as the ampere. The wire 1 centimeter away from a unit magnet pole is in a field of unit strength having a line per square centimeter, or 6.45 lines per square inch, and the unit current might have been defined as that current which, when flowing through a straight conductor 1 centimeter long at right angles to a magnetic field of one line per square centimeter density, caused the conductor to be pushed to one side with a force of 1 dyne. Inasmuch as doubling the current doubles the force, or doubling the field strength doubles the force, it may be stated generally that a conductor carrying current across a magnetic field has a force acting on it that, measured in dynes, is equal to the product of the current strength in C. G. S. units times the length of the wire in centimeters, times the strength of the magnetic field in lines per square centimeter.

Applying this rule to our armature, the current strength in each wire is $\frac{i}{10}$ units, since i is in amperes. The length of wire in the magnetic field is L inches for each wire and there are $\% Z$ wires in the field, so the length in inches is $\% Z L$ and in centimeters $\% Z L \times 2.54$. The strength of the field in lines per square centimeter is $\frac{\mathbf{B}_g}{6.45}$. Hence, the force acting in dynes on the rim of the armature is $\frac{i}{10} \times \% Z L \times 2.54 \times \frac{\mathbf{B}_g}{6.45}$ dynes.

Now, these wires are rotated S revolutions per minute, so the inches they move per second would be $\pi D \times \frac{S}{60}$; or, in centimeters, $\pi D \frac{S}{60} \times 2.54$. Multiplying the dynes of force by the centimeters through which the force acts gives the ergs of work; hence, the work in ergs required to drag the conductors through the above field for 1 second is

$$\left(\frac{i}{10} \times \% Z L \times 2.54 \times \frac{\mathbf{B}_g}{6.45}\right) \left(\pi D \frac{S}{60} \times 2.54\right)$$

But 10^7 ergs make a joule and a joule per second is a watt; so the number of watts required to drag the above conductors is

$$\left(\frac{i}{10} \times \% Z L \times 2.54 \times \frac{\mathbf{B}_g}{6.45}\right) \left(\pi D \frac{S}{60} \times 2.54\right) \frac{1}{10^7}$$

which reduces to

$$\text{watts} = \frac{\% \pi D L \mathbf{B}_g \times Z i \times S}{10^8 \times 60}$$

This is exactly formula **4**, which is the number of watts developed in the armature, and the above is the watts required to drag the conductors through the magnetic field when they are carrying current. Since the two are equal, it shows that there is no loss in converting mechanical into electrical energy. The losses of a dynamo occur before the conversion takes place, as in friction, core losses, windage, etc., or after the electrical energy is developed, as in resistance losses or current to excite the fields.

LIMITING OUTPUT OF CONSTANT-POTENTIAL DYNAMOS

41. Constant-Potential Dynamos.—The total E. M. F. generated by a machine depends on the number of conductors, the speed, and the magnetic flux. As all these qualities are usually kept nearly at the same value at all times in closed-coil generators, the E. M. F. of such machines remains nearly constant. Dynamos of which this is true are called **constant-potential machines,** in distinction from constant-current machines, which have already been defined.

The electric power that a machine is developing, usually termed its *load* or *output*, depends on the product of its E. M. F. and the current. To vary the load of a constant-current machine, the outside resistance is varied, and with it the E. M. F. generated is altered, usually automatically by a regulator, so that $\frac{E}{R}$ will remain constant. With a constant-potential machine, the current must be varied in order to vary the load. This is done by altering the resistance of the external circuit, because from Ohm's law, $I = \frac{E}{R}$; hence, if E is constant, I will vary inversely as R varies. The load on a dynamo changes, therefore, with a change in the resistance of the outside circuit—increasing directly with R in the constant-current dynamo until the maximum E. M. F. that the machine is able to maintain with the particular current the machine is made to give, is reached; while with the constant-potential machines, the load increases as the outside resistance decreases until the maximum current that the machine will safely generate is reached.

In the constant-current type, the maximum E. M. F. of the machine is, of course, fixed by the number of face conductors on the armature, the speed, and the magnetic flux. The magnetic flux is limited by the size and permeability of the field magnet, and the amount of wire on the armature is limited by the room thereon. A constant-current machine

when overloaded is simply unable to maintain the current at the particular value designed, and no injury can result from such overload.

42. Factors Limiting Output.—When the outside resistance of a constant-potential machine is greatly reduced, an excessive flow of current occurs and the dynamo may be injured in two ways: The large current may generate such great heat in the armature conductors as to injure them or their insulation; or, the large current may cause sparking at the commutator, and thus roughen or burn its surface, impairing the further use of the machine. These two limits to dynamos are often called the **heating** and the **sparking limits.**

HEATING OF ARMATURE

43. The heat developed in a conductor is, in watts, equal to the square of the current in amperes multiplied by the resistance; so, in order that the heat may be limited, the resistance of armature windings must be kept very low. It is not so much the heat developed in the windings that causes the trouble as the resulting temperature, and the temperature of a body depends not only on the rate at which heat is supplied to it, but also on the ability of its surfaces to radiate, or otherwise get rid of, the heat. Well-designed armatures have air passages through the laminated cores and also through the windings on the ends to assist in dissipating the heat developed, and such armatures are said to be ventilated. It will be noticed that the armature heating is not only due to the I^2R *loss*, as the heat developed in the windings is termed, but also to eddy currents and hysteresis in the armature core; these last are practically constant, regardless of the load, while the I^2R loss obviously changes with the square of the load in constant-potential generators.

44. It is customary to design modern dynamos so that the heating on a 10-hour continuous run with a constant load is such that the temperature of the armature is raised about 40° to 50° C. above the temperature of the surrounding air.

It has been found that insulating material under a constant temperature above 60° to 70° C. is slowly destroyed, and taking ordinary room temperature as 20° C., this leaves a safe rise of from 40° to 50° C.

Calling the load at which the temperature rise reaches the limit set as *full load*, the load at which sparking will occur should not be less than 20 or 40 per cent. over this, and preferably at 50 per cent. overload. Many well-designed machines will stand about double full load without serious sparking. A dynamo thus designed and rated can safely stand a continuous load at its full-load value, or a considerable overload of short duration or a momentary overload of 50 per cent. or more, as the case may be, without any damage whatever.

SPARKING AND COMMUTATION

45. Commutation is the process that occurs when a coil comes into connection with a brush. The primary action is the conducting of the current to or from the windings by the

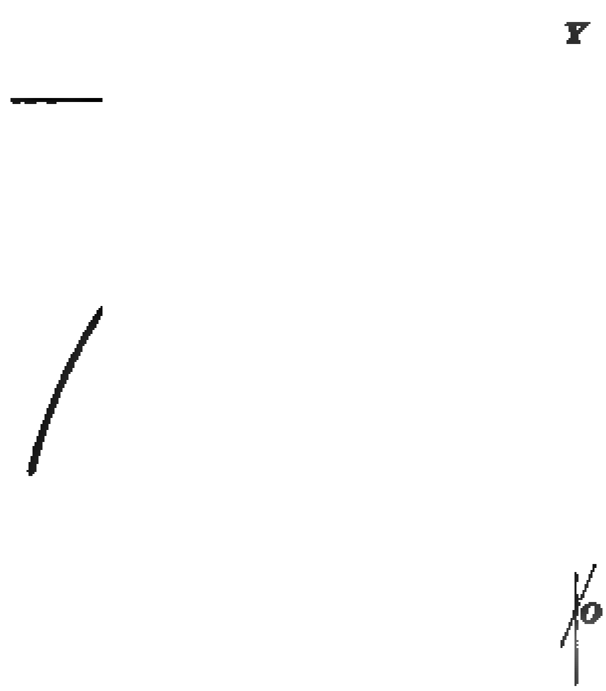


FIG. 15

brush, but in closed-coil armatures this has been shown to be accompanied by the reversal of the current in the coil during the time of this collection of the current. Under

certain conditions this reversal of the current in the coil may not be completely or properly accomplished in the time the segments pass a brush and undesirable sparking occurs, which tends to roughen and otherwise injure the commutator surface, thus aggravating the difficulty of collecting the current.

Fig. 15 is a diagram of a portion of a single, parallel, ring-wound armature in which the directions of the currents in the coils are marked. Observing the direction of these arrows, it is clear that as the coils pass from left to right of the brush, the current in them is reversed; it will also be noticed that the coils while under commutation are short-circuited by the brush.

46. On account of the self-induction of a coil of wire, the reversal, or in fact any change of the current flowing through the coil, causes a self-induced E. M. F. that is of such direction as to oppose the change of current; further, the value of this E. M. F. is proportional to the rate of change of current. It is clear that the current cannot be instantaneously reversed, otherwise an extremely high self-induced E. M. F. would result. The current in a coil when short-circuited by a brush does not immediately die down to zero, but is maintained by the self-induced E. M. F., unless some provision is made to stop it by overcoming this E. M. F.

47. Suppose the brush, Fig. 15, were placed on the line $O\ Y$; that is, in a position where the coil under commutation is entirely out of the magnetic field; and suppose the current to be 100 amperes in the brush, or 50 amperes in each of the two paths in the winding leading to it. Suppose, further, that the coil F under commutation, as shown in Fig. 16, is about to pass out from the brush, and that on account of the self-induced E. M. F. the current in the coil has only decreased from 50 to 40 amperes. Putting the values of the currents and their directions on the diagram, it is seen that about 90 amperes is forced to flow from segment t to the brush through a small and rapidly diminishing area of contact. As this area is small, its resistance is comparatively

high; and as the current density is abnormally high, the heat developed at the tip of the brush may be so great as to melt the commutator segment and the brush, also, if of metal. But this is not all. The segment t an instant later passes out from under the brush, and the circuit from t to the brush, with 90 amperes flowing in it, is broken. This breaking of the circuit will be accompanied by a bright spark that is somewhat destructive; and inasmuch as it is repeated with each segment at each brush, the trailing tips of the brushes are soon burned away, and also the trailing edges of the segments. When the circuit from t to the

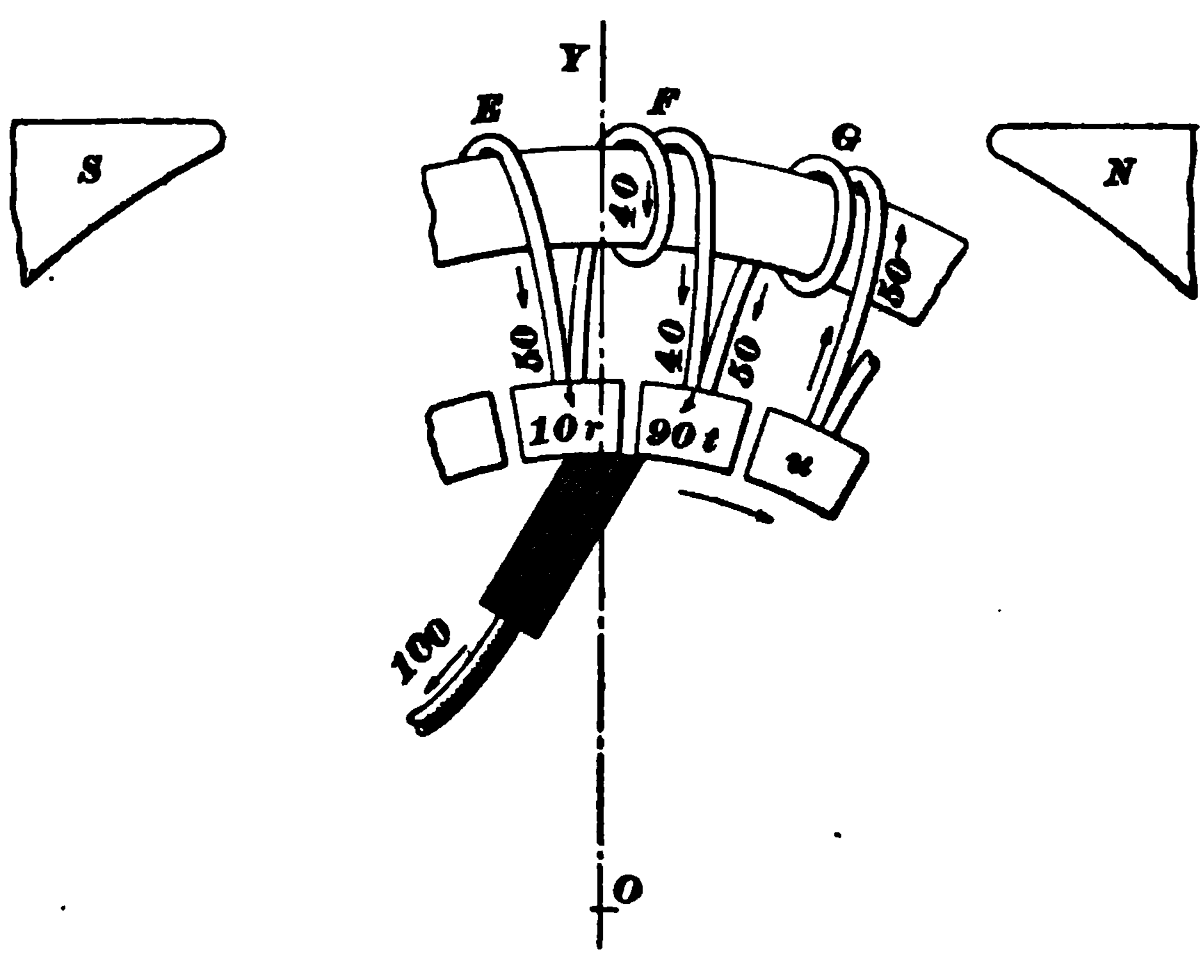


FIG. 16

brush is opened, a current of 50 amperes must flow from right to left through the coil F, and the change in current from that shown in the figure is from -40 to $+50$, or 90 amperes. If this change is accomplished in a very short interval of time, the rate of change will be great and the E. M. F. of self-induction will be considerable. This E. M. F. will display itself at the terminals of the coil F, or between the segments r and t; but since r is in intimate contact with the brush, there will be but little potential difference between them, and practically the whole of the E. M. F. self-induced in the coil F will exist between the brush and the segment t.

As the current flowing between t and the brush is throttled by the rapidly decreasing area of contact, the E. M. F. of self-induction rises; and if it becomes sufficient to maintain the current through the air, visible sparking will result.

It must be remembered that the E. M. F. that causes the sparking is that which is self-induced in the coil by the current changing therein, and is not due to the cutting of lines of force by the face conductors.

48. Use of High-Resistance Brushes.—It will be observed that since a considerable current is flowing from t to the brush through a small contact area having an appreciable resistance, an appreciable E. M. F. will be required to maintain this current between the brush and t. There can be but little E. M. F. between the segment r and the brush, as the contact between them is good; so it follows that the E. M. F. between the brush and t is also displayed between t and r. This E. M. F. is opposed to the current flowing through the brush-contact resistance, because it represents the E. M. F. necessary to overcome the resistance, and the tendency, therefore, is to divert the current flowing from t to the brush and make it take the path through coil F instead; in other words, to reverse the current in F. This resistance of the brush-contact area tends to assist in the reversal of the current in the coils under commutation, and consequently tends to decrease sparking. To make this effect more marked, brushes of high specific resistance are used—such as graphite, carbon, woven brass or copper gauze, all of which are superior in action to leaf-copper or strip-copper brushes.

49. Commutating Fringe.—Another way of overcoming the self-induced E. M. F. is by opposing it by an E. M. F. induced in the coil under commutation by its face conductors cutting across a weak magnetic field, or *fringe*, at the edge of the poles. The position of the coil under commutation is determined by the position of the brushes, and these are usually arranged, so as to be adjustable, by mounting them on a rocker-arm.

Suppose that the brush, Fig. 15, were rocked toward the left until the coil under the brush approached the south pole. The E. M. F. induced in it during the short circuit would be exactly similar to that in the coils to its left, so that the reversal of the current would not be assisted; but if rocked forwards to a position such as $O X$, that is, in the direction of rotation, the coil under commutation approaches a pole of opposite polarity from that it has just left, and the E. M. F. induced by the magnetic field will oppose that self-induced during the reversal

The magnetic field between poles is not zero, except along the neutral plane $O Y$, but gradually shades off from positive under a north pole to zero and to negative under a south pole. It follows, therefore, that for purposes of commutation, a field of just the right strength may be found between the poles by properly adjusting the position of the brushes.

50. It has been stated that the value of the self-induced E. M. F. depends on the rate of change of current. Since the speed of the machine is usually constant, the time of reversal remains constant; so the rate of change of current depends on the value of the current output of the machine. It therefore follows that the position of the brushes, as $O X$, Fig. 15, having been found such that at a certain load the reversal of the current is properly accomplished, as shown by the absence of any sparking, the position is correct for this particular load only, and if the load is greater, the brushes must be rocked further forwards and vice versa.

Dynamos using metal brushes (and some with carbon brushes) usually require a shifting of the brushes with load variations; and this being undesirable, carbon or other high-resistance brushes are now chiefly used on account of their additional assistance in reversing the current. In well-designed machines, the carbon brushes are set so that the current can be sparklessly commutated under full load, and it is usually the case that under no load the sparking is scarcely visible and not injurious. That the machine sparks

at all under no load is due to the fact that the coil under commutation is of very low resistance and is short-circuited by a brush while it is in a field and generating an E. M. F. Small as is this E. M. F., the resistance of the circuit being very small, $\frac{E}{R}$ may be quite large and a considerable local current thus induced in the short-circuited coil, only to be broken when one of the segments in which it terminates leaves the brush. This breaking of the circuit causes sparking in exactly the same manner as before.

51. The term *sparking* is not confined to its literal meaning, any improper commutation being given that name. Sometimes the current density in the trailing tip becomes so high that the carbon brushes may become red hot and glow in spots, or the copper in contact with the brush may be melted and rubbed off by the brush without visible sparking. Sparking may also manifest itself in blackening the commutator, indicating that the current density is high enough to disintegrate the brush or roughen the commutator surface.

52. Requirements for Sparkless Commutation.—In designing a dynamo, it is necessary, in order to insure good commutating qualities, to keep down this self-induced E. M. F. This can generally be done by the following means:

1. Make up the winding with a large number of armature coils, so that the inductance of each may be small. The current will then be reversed in detail, as it were, in the windings.

2. Use a winding having a sufficient number of paths, so that the current per path will not be too great.

3. Use as thick brushes as is practical with a moderate speed of commutator surface, so that the time of reversal will not be too short. Brushes that are too thick cause sparking, because the neutral region is usually quite narrow, and if a brush short-circuits a coil while in anything but a very weak field, a strong current will be set up in the coil. Again, where a number of coils are simultaneously under

commutation, they induce E. M. F.'s in each other by mutual induction, which also may cause sparking.

53. In the foregoing, such causes of sparking as roughness of the commutator, vibration of the machine causing the brushes to be jarred from contact with the commutator, etc., have not been considered, because these are mechanical imperfections in the individual machines, and should be corrected. It is not always an easy matter, however, to distinguish whether sparking in an individual case is due to mechanical imperfections or to electrical ones. Often some electrical difficulty will cause slight sparking, which may in turn so roughen the commutator as to make the trouble appear as though the cause were entirely mechanical.

ARMATURE REACTION.

54. By **armature reaction** is meant the magnetic interference of the armature with the magnetic field in which it rotates. To thoroughly understand the magnetic effects of the armature, it is best to first consider those of a single wire in a magnetic field.

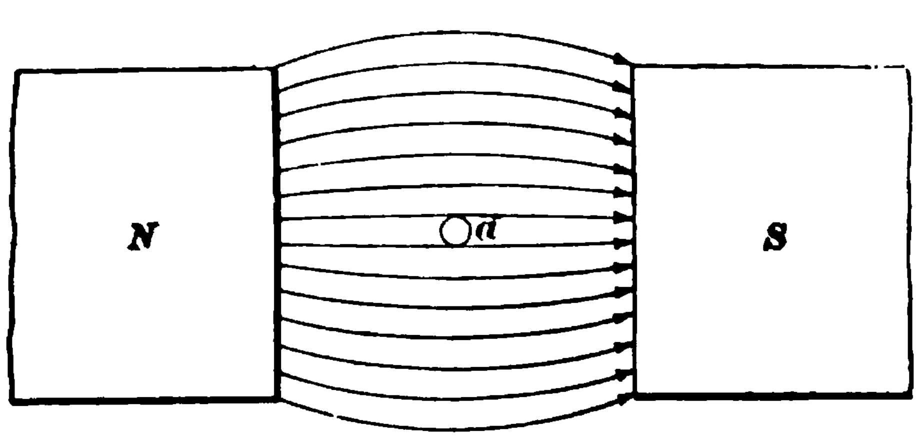


FIG. 17

Suppose that the arrows in Fig. 17 represent the magnetic lines of force flowing between the pole faces of the magnet NS, and let a represent the cross-section of a wire lying at right angles to the lines. So long as no current flows in the wire the magnetic field will remain as shown; but if the wire carries current, say downwards through the paper, the current will tend to

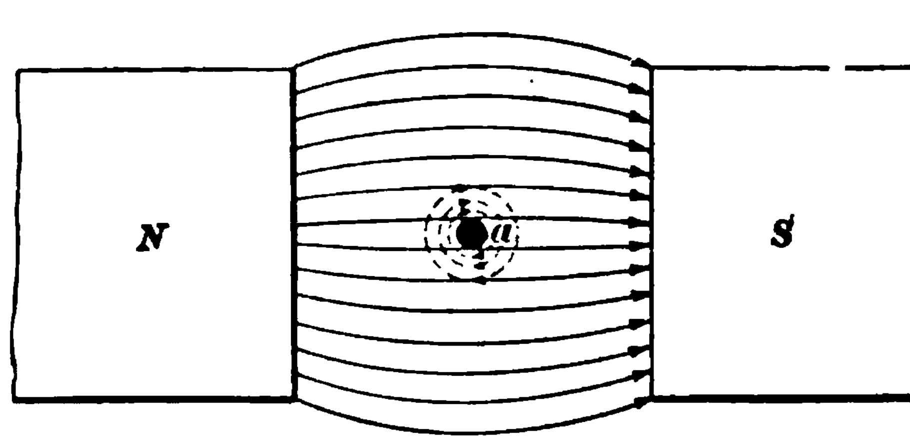


FIG. 18

set up lines of force around it, as shown by the dotted circles in Fig. 18. It will be noticed that these lines tend to oppose the original field below the wire and tend to assist it above the wire; the resultant effect is

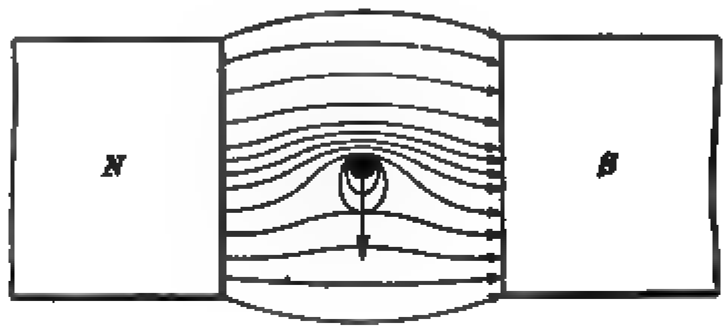


FIG. 19

that the field is distorted, as shown in Fig. 19. These magnetic lines act like so many fine elastic bands, with which conception the effect of the current in Fig. 19 can be easily seen, for the lines of force appear crowded upwards, indicating that the conductor is pushed downwards, as shown by the arrow.

55. The action of the conductors in the air gap of a dynamo is very similar to that described for a single wire, except that since there are more conductors their action is more marked. If there is no current flowing in the face conductors, the magnetic lines will cross the air gap radially.

FIG. 20

In Fig. 20 is shown a diagram of the poles and armature of a bipolar machine, in which the poles are not magnetized by the field coils, but the armature conductors are shown carrying currents, and magnetism is set up by the armature

currents, as indicated by the dotted lines. In this diagram, and in those that follow, a conductor marked with a dot indicates that the current is flowing in it upwards from the paper, while the solid black circles indicate that the current therein is downwards into the paper.

Applying the rule for the direction of the magnetic lines surrounding these conductors, it is seen that each pole piece is magnetized so that the lower side is a north pole while the upper side is a south pole. The chief reluctance of these magnetic circuits is in the air gap, the paths in the iron being short; in the practical case it is not far from the truth to consider the reluctance of the iron negligible. It will be seen, then, that those magnetic lines which flow from the tips of the poles surround or link with the most turns and therefore have the most ampere turns displayed along their path. If the reluctance of the iron be neglected, the reluctance of all the concentric magnetic paths or circuits will be the same, so that the flux set up will be proportional to the number of turns included by the circuit. It is thus seen that the strength of the field in the air gap is greatest at the tips, reducing to zero at the middle of the poles.

56. Now imagine the field circuit to be established; the combined action of both the armature current and the field current will be as shown in Fig. 21. This will be seen to be quite similar to Fig. 19, for the magnetic lines in the air gap are pushed toward the pole tips *c* and *f* by the action of the armature currents; the conductors will therefore have a force acting on them contrary to the direction of rotation indicated by the arrow. Since this force is contrary to the direction of rotation, it will require power to drive the armature; this mechanical power is absorbed only to appear as electrical power in the armature windings. If the armature were to revolve in the direction of the force, instead of against it, some mechanical force would be required to act against that of the conductors so as to keep the speed uniform; the armature would then be running against this force and would supply mechanical power. This

is the action of an electric motor, and the power obtained mechanically must be supplied electrically to maintain the armature currents against the E. M. F.'s that will be set up by the cutting of lines of force by the face conductors. Not

FIG. 21

only are the lines of force in the air gap displaced by the action of the armature currents, but they cross the air gap slightly on the slant; this produces the pull, or drag, on the conductors and the **torque,** or twisting force, of the armature.

57. Magnetization at Pole Tips.—In Fig. 21, it will be noticed that the strength of the magnetic field varies uniformly from *a* to *c* or from *c* to *f*. To find the strength of field at any point in the air gap as, say, at *a*, it is necessary to take the sum of the strength of field that would be set up uniformly over the whole pole face by the field currents, and the strength of field shown in Fig. 20. This sum will give the combined field due to both field and armature currents. It will be noticed that the direction of the field at *a*, Fig. 20, is opposed to that due to the field currents, hence the numerical difference of these two field strengths is the strength of the field at *a*, Fig. 21. It is very undesirable to have the field very weak at the pole tip, and in practice the field set up by the armature currents is never as strong as that due to

the field windings. At the tip c, the field due to the armature currents is in the same direction as that due to the field currents, so this pole tip is strengthened as shown, being numerically the sum of the strengths of the two fields.

It will be noticed that since, in Fig. 21, the field has been shifted, that the neutral region is also shifted and the brushes on this account, as well as on account of sparking, should be shifted in the direction of rotation, or given a lead, as it is called. This will cause the diagram of the face conductors to appear as in Fig. 23.

58. Cross Ampere-Turns and Back Ampere-Turns. In Figs. 20 and 21, the currents in the armature conductors flow so as to form an electromagnet of the armature, and magnetize it about an axis $a\,b$, Fig. 22. As it is immaterial how the armature is wound, so far as the magnetic action is concerned, at the instant shown it may be considered as being made into a winding as indicated by the dotted lines in the figure. Consider Fig. 23,

FIG. 22

in which the brushes have been given a lead of an angle r, and are on the line $x\,y$. Consider the winding as connected up into two coils wound at right angles, as shown, one coil having $a\,b$ as its axis and the other having $N\,S$ as its axis. The coil whose axis is $a\,b$ tends to set up a field, as in Fig. 20, making the upper side of the armature a north pole, and the lower side a south pole. Since this is directly across the main magnetic path in the armature, it is known as the **cross-magnetism**, and the turns setting it up, which are those included within the angle k, are known as the armature **cross-turns**. The ampere-turns setting up the cross-flux, the product of the armature current per wire and the

cross turns, is known as the armature **cross ampere-turns.** The direction of the currents in the coil whose axis is NS is such as to cause its ampere-turns to oppose those of the field coils, and for this reason these turns are called the **armature back turns;** and the product of these turns and the current in each armature conductor is known as the armature **back ampere-turns,** or **counter ampere-turns.** It will be seen from this figure that the angle of lead of the brushes r is equal to the angle m; and further, that from the construction, the back turns are those that lie within the angles r and m, or within the double angle of lead of the brushes. The remainder of the armature turns are the cross-turns, and are included within the angle k.

FIG. 28

59. Considering Fig. 20, it will be seen that while all the armature turns in this case are cross-turns, the brushes not being given any lead, yet all these turns are not available for setting up the flux in the poles; only those that lie beneath the pole faces are effective in setting up a cross-flux. Those that lie between the poles must set up the lines through such a long path in air that the flux they produce is practically negligible.

The armature cross-turns may be defined practically as those that lie beneath the pole faces. The cross ampere-turns tend to weaken the strength of the field under one half the pole piece, and tend to strengthen it under the other; and since the weakening effect is equal to the strengthening, the total flux on which the voltage depends is not changed. That the flux remains the same would be absolutely true, were the ampere-turns for the air gap only

to be considered, for the permeability of air is constant. But since some of the ampere-turns are required for iron, and since the permeability of iron decreases as the density increases, the magnetizing effect is usually not quite as great as the demagnetizing, because the higher density in the iron parts near the strong pole tips requires a greater proportionate number of ampere-turns. This will be more fully explained in connection with the design of a machine.

60. For multipolar generators, the action is much the same. For both bipolar and multipolar generators with drum windings, the total armature ampere-turns per magnetic circuit may be defined as the product of the number of turns per pair of poles and the current in each turn. Since there are two face conductors per turn, this may be expressed as follows:

$$\text{Armature ampere-turns} = \frac{Zi}{p} \qquad \textbf{(9)}$$

Where Z = number of face conductors;
i = current in each conductor;
p = number of poles

This represents the value of the ampere-turns on an armature, with the line $a\ b$, Fig. 22, as an axis. If this quantity is multiplied by the percentage of the armature covered by poles $\%$, the numerical value of the cross ampere-turns is obtained thus:

$$\text{Cross ampere-turns} = \frac{\% Zi}{p} \qquad \textbf{(10)}$$

The back ampere-turns are not as prominent as the cross ampere-turns, since they are fewer, but they may be computed thus:

$$\text{Back ampere-turns} = \frac{2rZi}{360}, \qquad \textbf{(11)}$$

where r is the angle of lead of the brushes in degrees. Applications of these formulas will be shown later in connection with the designs of a multipolar dynamo.

61. It has been shown that the brushes must be shifted ahead of the neutral line in order to bring the short-circuited armature coil into a field of sufficient strength to set up the proper E. M. F. to reverse the current in the coil. It is easily seen that as the armature current increases, the strength of the field in which commutation occurs is decreased by the cross-magnetizing force, so that the brushes must be shifted still farther ahead to reach a field of the proper strength. This increases the angle of lead and the back ampere-turns become greater and greater, further weakening the field; if the armature current is great enough, the brushes might be shifted any amount without reaching a sufficient field for commutation. The armature reaction then limits the amount of current that the armature can supply without an excessive shifting of the brushes. This limit of the output is the sparking limit.

62. General Effects of Armature Reaction.—Armature reaction does three things:

1. It inclines the magnetic lines in the air gap, producing the torque or twisting force. This is absolutely essential for the proper action of the machine.

2. It shifts the field in the direction of rotation in a dynamo, due to the cross-magnetizing force of the ampere-turns beneath the pole faces. This effect may be lessened by increasing the reluctance of the path of the cross-flux. One of the chief methods of doing this is by saturating magnetically the pole tips and armature teeth, as will be fully explained in connection with the design of a generator. The cross ampere-turns may be neutralized by placing on the poles, windings in series with the armature winding and arranging them to set up a flux in a reverse direction to that of the armature winding.

3. It tends to weaken the field strength due to the counter-magnetizing forces. This effect is easily neutralized by placing on the magnet cores series-windings of the proper number of turns.

CONSTRUCTION OF THE ARMATURE

CONSTRUCTION OF CORE AND SPIDER

63. The **armature core,** as it is called, consists usually of a number of thin punchings of a special grade of iron, or steel, selected especially for the purpose on account of its having high permeability and also being subject to only a moderate loss per cubic inch by hysteresis. Occasionally, fine iron wire and iron strips are used, but these are so rare as to be hardly worthy of notice. The punchings are usually from .014 to .03 inch thick, although .06 inch has occasionally been used. As has already been explained, this lamination of the core is necessary to prevent the formation of eddy currents within the core; and since the loss caused by eddy currents varies with the square of the thickness of the punchings, it is evident that thin stampings are much better than thick ones. The losses in punchings less than .02 inch, or 20 mils thick, are so small that the additional cost of using much thinner material does not result in a gain sufficient to compensate therefor.

These punchings must be supported on a shaft. They may be slipped directly thereon or they may be mounted on a spider, which, in turn, has a hub through which the shaft is pressed. In bipolar machines, the flux passes from diametrically opposite points through the core; therefore it is best to have as small a central hole in the punchings as possible; they are

FIG. 24

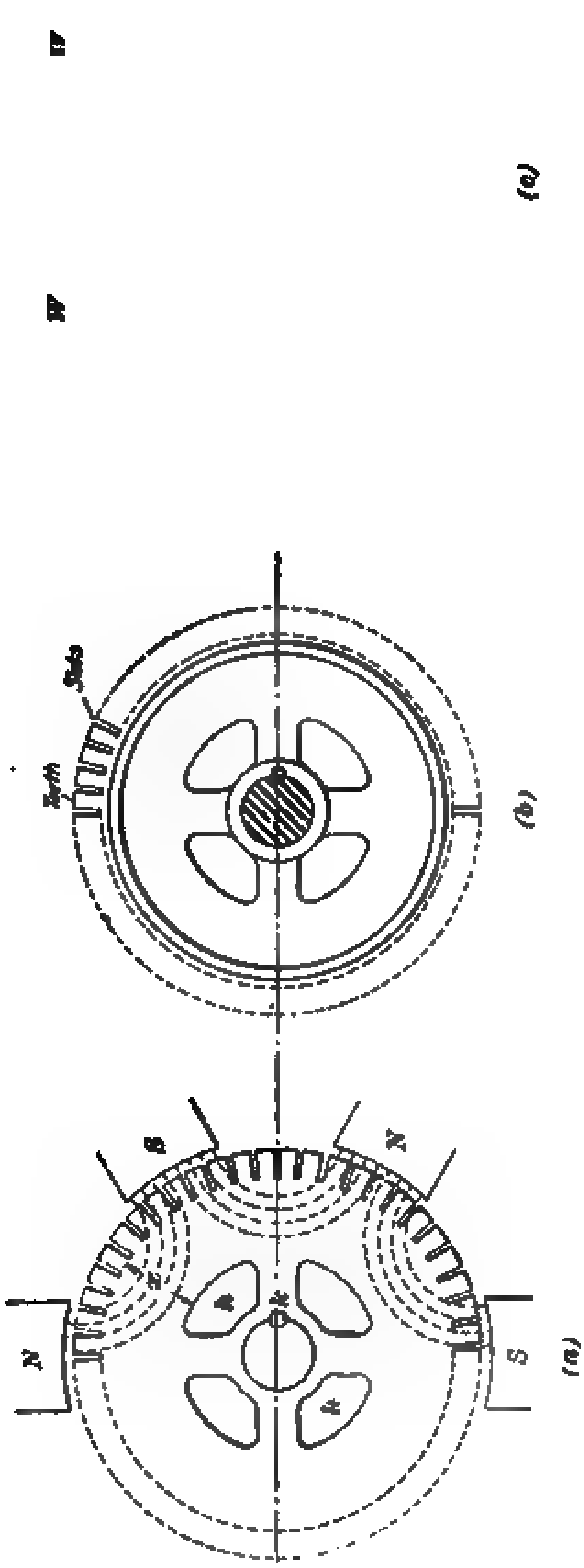


FIG. 25

in this case simply slipped on the shaft, as shown in Fig. 24. The punchings are held firmly in place between two end plates, *a*, *a*, usually of cast iron, which are clamped between a shoulder *c* on the shaft and the nut *b*. To prevent the disks from turning, a key inserted in the keyway *d* projects above the shaft into a suitably cut nick in each punching. The nut *b* need not be hexagonal; it is often round, and can be well screwed up by a pipe wrench. In another construction the nut is replaced by a tight sleeve, which is pressed on with a hydraulic or other press.

64. Fig. 25 shows the construction of a multipolar armature in which the disks are punched, as shown at (*a*), and slipped on the shaft between two end plates *E*, *E* (*c*), one of which is held by the shoulder *t*; the other is preferably pressed on

and held by a nut *n* on the shaft. It will be noticed that the path of the flux from pole to pole is along a short cord in a multipolar armature, rather than along a diameter, as in the bipolar; and, further, the poles in the former being smaller with the same diameter, a large radial depth of iron *x* is not required to convey the magnetic flux. In other words, using the same diameter of core disks, the dimension *x* may be decreased as the number of poles is increased. The holes *h* are therefore punched out, leaving the arms *k* for supporting the rim, which, with the teeth, constitutes the real armature core. This construction greatly lightens the armature and permits the circulation of air through the core to assist in carrying away the heat developed therein. This keeps down the rise in temperature or, with a given rise in temperature, permits a greater load. The end plates *E*, *E* should have a long hub to firmly attach them to the shaft. At (*c*) these end plates are shown with extensions for supporting the windings *W*, *W*.

65. Armature Spiders.—The construction shown in Fig. 25 saves somewhat in labor by avoiding the use of a spider, but it is more wasteful of armature iron, since the central part of the disks, if punched out in a single piece, would doubtless be used for smaller armatures It is also objectionable in that the shaft cannot be removed without disturbing the punchings.

When dynamos are direct-connected to engines or waterwheels, it is customary to supply the armature complete without the shaft, the engine builder supplying this with the engine; it is desirable, therefore, to be able to build the armature without a shaft.

66. An armature core intended for a ring type of winding is shown in Fig. 26. The disks are supported on a four-arm spider made in two parts, which are clamped together by the nut *n* on the shaft. For ring windings, the spider arms *s*, *s'* are made very thin, say from $\frac{1}{4}$ to $\frac{1}{2}$ inch thick, so as not to interfere with the windings on the inside of the core. To each part of the spider, an end ring *r*, *r'* is

attached; these clamp the disks together; the arms projecting beyond the rings in the form of wings are merely added to obtain additional strength. A small key *k* in one of the spider arms prevents the disks from turning on the spider, while another key *k'* prevents the spider from turning on the shaft. This style of spider has been used for ring armature for arc-light dynamos. One objection to it is that the hub is in two parts, which interferes to some extent with removing or inserting the shaft, after the armature has been built.

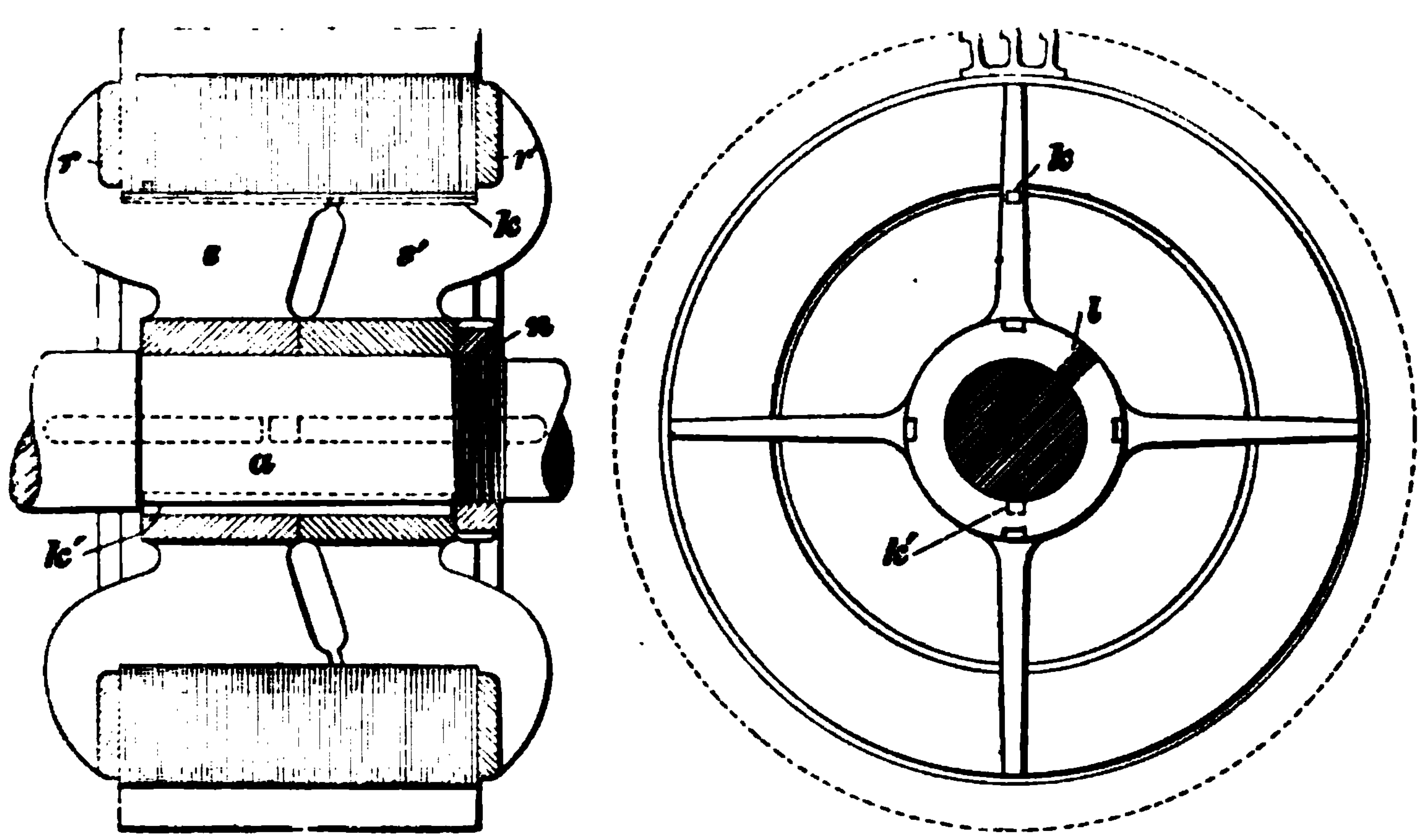


FIG. 26

67. In order that the disks may be readily slipped over the spiders, which is done before they are put together, each spider is provided with two lengths of arm. Opposite arms are of the same length, as seen in full lines in the cross-sectional view of Fig. 26, but two are shorter than the other two, as is indicated by the dotted lines at *a*. Each spider may thus have a number of disks laid over it, up to the full extent of the longer arms, and the two spiders are then pressed together with clamps. It is better to leave a small clearance space between the ends of opposite arms, and allow the hubs to meet on the shaft. After the disks are all in place, the spiders containing them are pressed on the shaft, and the nut *n* is screwed up to hold them. A setscrew *l* should be used to prevent the nut from loosening.

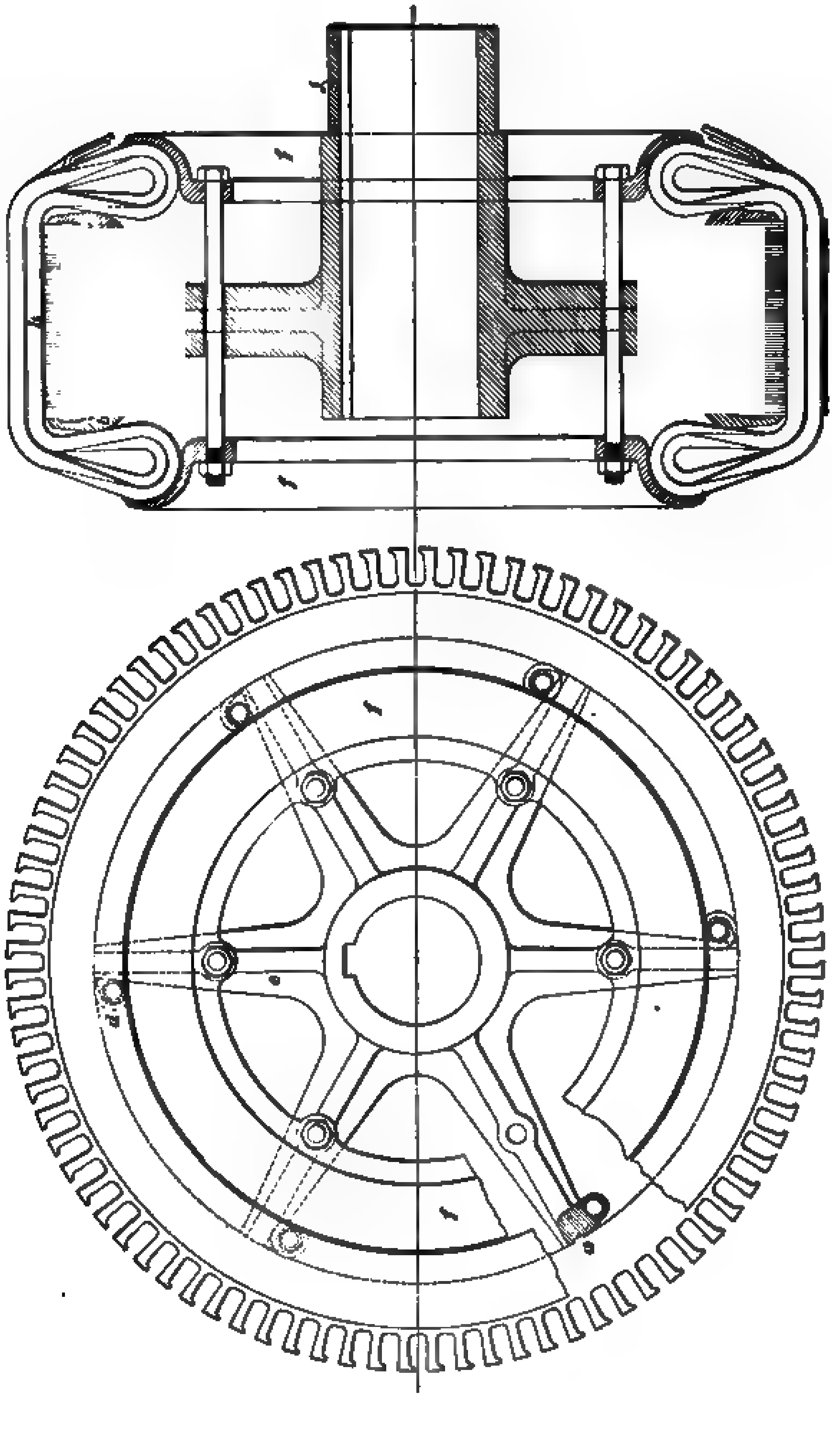


FIG. 27

In small, ring-wound armatures the spiders are usually made of bronze, to prevent leakage of the magnetism through them across from pole to pole, for such flux would set up in the wires on the inside of the core E. M. F.'s directly opposed to those induced in the face conductors. On larger machines this is hardly important enough to warrant the expense of large bronze castings.

68. Fig. 27 shows an armature core mounted on a spider, which can be removed from the shaft without taking the armature apart. Here the spider consists of two parts, the spider proper and a small end ring *c* for clamping the disks, which is attached to the spider by tap bolts *d*. Instead of using a key for keeping the disks from turning, they are punched with a tongue shown at *a*, which fits into a keyway cut into one of the spider arms. The arms are wider and thicker than in Fig. 26, for the winding being of the drum type does not pass through the center of the core and is therefore not interfered with by heavy arms. The end rings on the spider, for clamping the disks, are strengthened by the rib *b*, which runs completely around, as shown.

In the section, the winding *h* is shown in place, the end connections being held and protected by the flanges *f*, *f*. It must not be thought that the section represents the shape of a coil, for the two sides of a coil (upper in one slot, lower in another) must be separated by the angular distance between corresponding points on adjacent poles, as has already been explained.

At *j*, the hub of the spider is shouldered down to receive the commutator, which is of the same style as that shown in Fig. 39. It will be seen that the completed armature is independent of the shaft, so that this construction is especially suited for direct-connected machines.

69. An armature core and spider for a large, barrel-wound, electric-railway generator are shown in Fig. 28. The spider consists of a hub and radial arms only, both the end plates being separate. The hub is cored out so as to leave only three points for boring out in order to reduce the

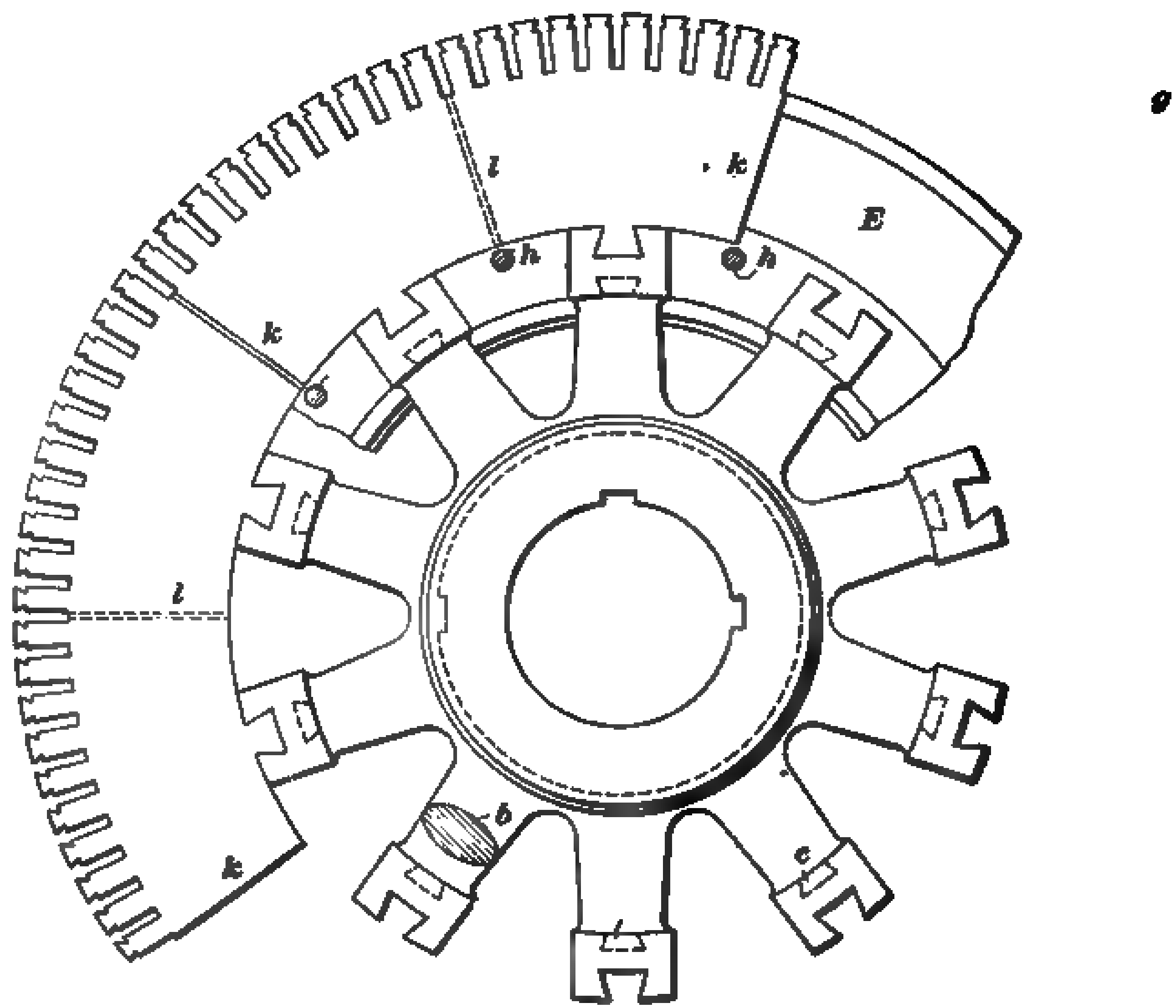


FIG. [illegible]

labor of machining. As in Fig. 27, the commutator spider is fitted on to an extension of the hub of the armature spider. The spider arms are elliptical in section, as shown at *b*, and are provided with heavy end-pieces having pockets *c* into which lead may be swaged for the purpose of balancing the armature. The armature end plates *D*, *E* are provided with flanges *f*, *f* that fit under the end-pieces of the spider arms. The end plate *D* has a flange *g*, which, being as large in diameter as the armature core, protects the windings supported by it from injury.

The armature core disks are made in five segments, the diameter being too great to admit the use of a single punching per disk, as is usually the case with smaller machines. Each segment has two lips, or dovetail projections, on its inner edge, which fit properly into recesses in the spider arm, as shown, the whole core being clamped firmly together by the bolts *h*. In assembling the disks, the joints between segments are broken; that is, if on one disk the joints are at *k*, *k*, on the next they will be at *l*, *l*, etc.

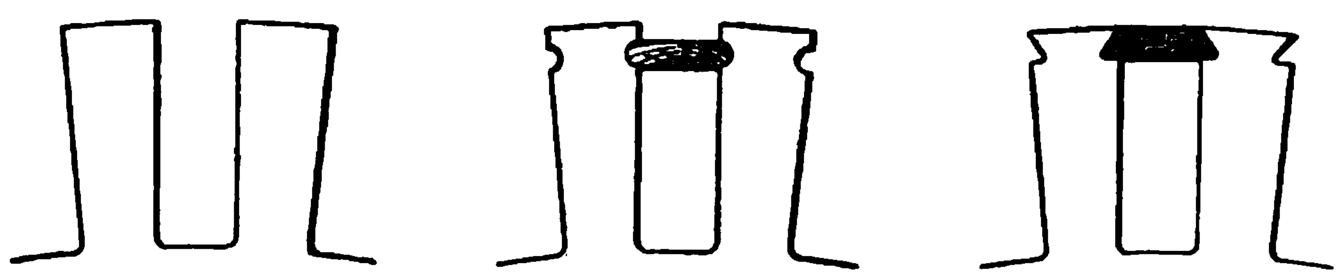
70. Ventilating Ducts.—It will also be noticed in the section of the core that openings *v*, *v*, *v*, Fig. 28, are shown between the disks. These are called **ventilating ducts,** or **flues,** and are air passages in the core formed by properly made spacers. These ducts are for the purpose of permitting air to be forced outwards through them by the centrifugal action, thus radiating the heat due to the armature losses. This causes the rise in temperature for a given load to be very much lessened, and therefore raises the heating limit of the machine; that is, it increases the load at which the machine will rise in temperature to such a degree as to endanger the durability of the insulating materials.

71. Smooth-Core and Toothed Armatures.—Armature cores are referred to as **smooth-core,** and **slotted** or **toothed,** according to whether the face conductors are upon the outside cylindrical surface of the core or are held in slots. Windings placed upon smooth-core armatures are usually called **surface windings.** In modern practice,

these are not much used because the output of a dynamo may be increased by using a slotted armature and also because the windings in the latter case are thoroughly protected and can be better insulated.

In winding a smooth-core armature, the core should first be carefully insulated and stout fiber driving pegs driven into properly cut recesses in the end plates, or core proper, for the purpose of guiding the winding and also for driving it against the reaction of the magnetic field.

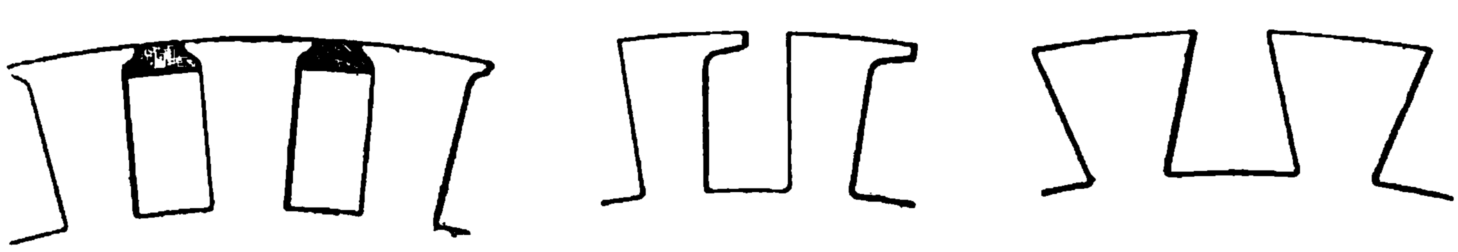
72. Armature Slots.—Armature slots are of a variety of shapes, some of which are shown in Figs. 29 and Figs. 30. At (*a*), Fig. 29, is shown a plain straight slot with parallel



(*a*) (*b*) (*c*)

FIG. 29

sides. This is the simplest and perhaps the most used of any. At (*b*) and (*c*) are shown modifications having nicks at or near the top into which fit retaining wedges of hard wood or fiber. These wedges not only protect the winding from injury, but take the place of wire bands, which are otherwise necessary, for retaining the winding in place against the centrifugal force due to rotation. Of course, on armatures using retaining wedges, band wires must be used on the end connections beyond the core.



(*a*) (*b*) (*c*)

FIG. 30

In Fig. 30 are shown some of the shapes of slots in which the teeth overhang. These types are usually resorted

to in order to keep the opening of the slot small and still have a liberal size of slot. A wide opening at the surface is objectionable when the length of the air gap between the pole face and the teeth is small, since in that case the magnetism passes across the pole face in tufts, see Fig. 31, and

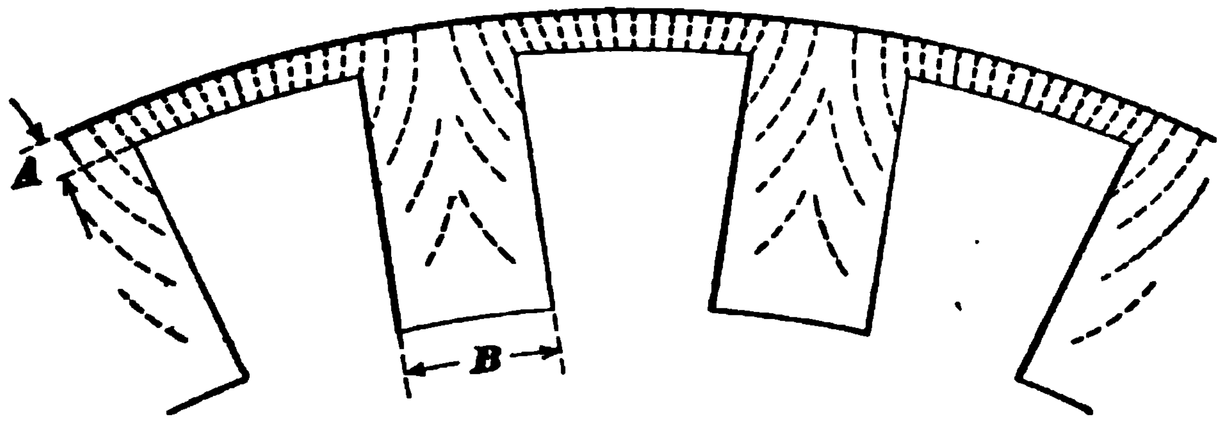


FIG. 31

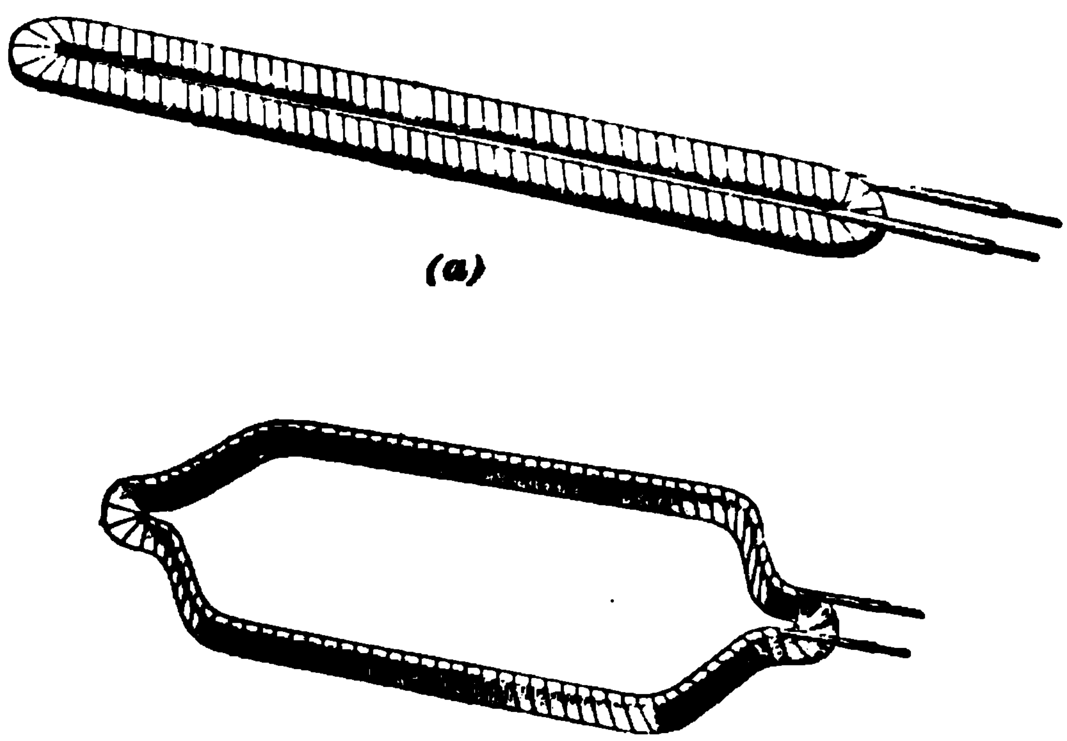
is then liable to set up eddy currents in the pole face because of the rapid passage of magnetic flux of varying densities across the face. When the losses incurred by these currents are objectionable, the pole pieces may be laminated, like the armature core, in which case the slot openings may be very wide without occasioning any material loss.

73. In this connection it may be stated that it has been found that where the average air-gap magnetic density is less than 35,000 lines per square inch, solid poles may be used if the length of air gap A is greater than $\frac{B}{3}$, but if not, the pole pieces should be laminated. If the air-gap density is about 50,000 or more, A should be greater than $\frac{B}{2}$ with solid poles.

Sometimes the slots are entirely closed at the tops and become holes near the periphery of the core. This construction thoroughly protects the windings, and does away with all liability of pole-face eddy currents, but is very objection able, because the armatures are difficult to wind in comparison to the open-slot type, and also because the self-induction of the coils is so greatly increased that it is difficult to prevent commutator sparking.

METHOD OF APPLYING WINDINGS

74. Construction of Coils.—The usual shapes of armature coils have already been shown. The barrel type of winding is now generally used, for it spreads the windings out on a rapidly moving surface and thus readily dissipates the heat developed by the I^2R losses. Coils of this shape,

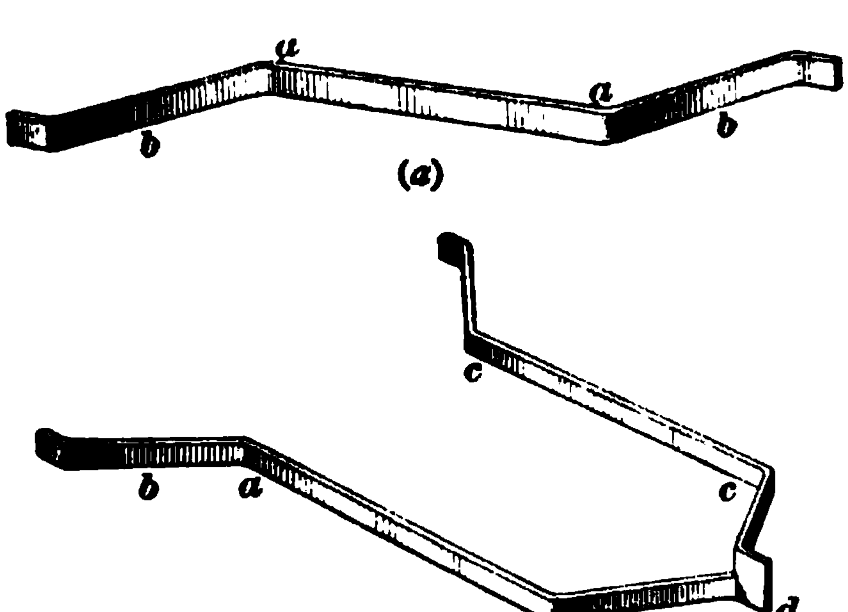


(a)

(b)

FIG. 32

where wound with wire of several turns, may be wound directly upon a frame, or form, having the peculiar shape of the finished coil, or they may be wound into a single loop, as shown at (*a*), Fig. 32, and afterwards put into a frame and pulled out into the shape shown at (*b*). Where the coil is made of a single turn of copper strip or of heavy round copper, the same process may be used, but the pulling-out frames are not satisfactory for heavier conductors. In forming coils of copper strip of, say, from $\frac{3}{8}$ inch to $1\frac{1}{4}$ inches in width, pieces of the copper may be bent as



(b)

FIG. 33

shown at (*a*), Fig. 33, then insulated and assembled on the armature, after which the proper ends are soldered together by a clip at *d*, forming a coil as shown at (*b*). In Fig. 33, parts *a a*, *c c* lie in the slots, while parts *b b* form the end connections. Some makers avoid the soldered joint at *d* by first bending the strip on edge into a long **U**; it is then clamped into a suitable cast-iron former, and the annealed copper hammered to the required shape with a mallet. When the coil is completely shaped the clamps are removed and the coil carefully taken out, so as to preserve its correct shape. It is then wrapped with cotton, or sometimes linen, tape $\frac{3}{4}$ inch wide, treated with armature varnish—a preparation consisting chiefly of linseed oil—and then baked in an oven at a moderate temperature.

75. Slot Insulation.—Before inserting the coils in the armature slots, the latter are insulated with a cell of mica, presspaper, or pressboard, oiled muslin, or a combination of these in the form of a thin sheet usually from .02 to .06 inch thick, shown at *b*, Fig. 34. The coil is then inserted in the slot and over it is placed a layer *a* of insulating material usually a little thicker than the cell. The upper coil is then inserted, the cell bent down over the upper coil, see Fig. 35, and finally the hardwood or fiber wedge pushed into place. It is, of course, evident that there are many satisfactory ways of insulating the coils, but the above serves as a typical example. It is very similar to the method used by several prominent manufacturers on their larger machines.

FIG. 34

76. For low-potential generators, say 125 or 250 volts, a very good slot insulation may be made up from two thicknesses of thin presspaper .01 inch or .015 inch thick with a layer of oiled muslin between them, the whole being stuck together with shellac; if this is bent into shape before it is dry, it is readily handled. Such an insulation is called a **sandwich.** If the potential of the machine is greater, very thin leaves of mica may be added between the sheets of presspaper until the desired insulating qualities are obtained. On arc-lighting generators, troughs, or cells, of mica, or micanite—a preparation of thin sheets of mica stuck together with shellac or other varnish—are used, but for potentials of 600 volts or under, such slot insulations are unnecessarily expensive.

FIG. 25

SHAFTS

77. Dynamo shafts must be somewhat stiffer than shafts for general machinery. The air gap of a dynamo is usually from $\frac{1}{16}$ inch to $\frac{1}{4}$ or $\frac{3}{8}$ inch, and if the shaft springs or deflects under the armature weight, the armature will become eccentric in the bore of the poles and thus shorten the air gap on one side and lengthen it on the other. The pole with the shortest air gap will naturally set up the greatest flux and therefore cause the greatest pull on the armature toward it. This exaggerates the trouble, for the excessive magnetic pull may cause the armature to be still further deflected from its central position and it may ultimately strike the pole pieces.

The diameter of a shaft for a given dynamo may be computed on either of the following rules with satisfactory résults: (1) The deflection of the shaft due to the weight of the armature and commutator should be between the limits .004 inch to .008 inch at the face of the armature. (2) The maximum fiber stress in the metal should be between the limits 5,000 to 8,000 pounds per square inch. The following formula, however, may be used for getting the approximate size of a shaft:

$$\text{diameter} = k\sqrt[4]{\frac{\text{watts}}{\text{R. P. M.}}} \qquad \textbf{(12)}$$

In which k may be taken from the following table for belted dynamos. For engine-type dynamos shafts are special and are usually made by the engine builders, the bore of the armature spider being made to suit.

TABLE I

VALUES OF k IN FORMULA 12

Kilowatts	k	Kilowatts	k
1	.90	50	1.10
5	.95	100	1.20
10	1.00	500	1.40

78. Having obtained the diameter by this formula, the stresses should be checked up, not forgetting those due to the pull of the belt, and the deflection of the armature core proper should be computed. The shaft should be made at least as large as the greatest value required by the limits adopted by the rules. Methods of computing the deflection or the maximum fiber stresses cannot be taken up at this point; they belong properly to the subjects of mechanics and machine design.

The shafts must be shouldered down to meet the requirements in the design, so that a shoulder or collar is provided at or near the inner side of each bearing to limit the endwise

motion of the shaft in the bearings. This end motion may best be limited in this way, for it is only at the bearings that wearing surfaces are supplied with oil.

BEARINGS

79. The size of **bearings** for dynamos is determined in the same manner as are other bearings, except that the constants for the formulas used are selected so as to give rather larger bearings than those for general machinery. Bearings for dynamos usually have a length of from three to four times their diameter.

Dynamo bearings are always made of the ring-oiling type; that is, the bearing is supplied with a reservoir for oil into which dip one or more rings that run upon the shaft, and thus supply the journal continually with oil.

COMMUTATORS

80. The **commutator,** as has already been explained, consists of a number of copper segments clamped together by suitable clamping rings, each segment being insulated from the others and from the clamping rings by mica or micanite. The brushes that serve to convey the current to or from the commutator rub on its outside cylindrical surface, which is turned true and smooth for this purpose.

Figs. 36, 37, and 38 illustrate three commonly used shapes of segments and their clamping devices. Fig. 36 illustrates the form of commutator used on the Edison bipolar dynamos, an early type of exceptional merit. It consists of a shell, or sleeve, *s* on which is screwed the ring *f*. A micanite cone, or ring, *i* is slipped on,

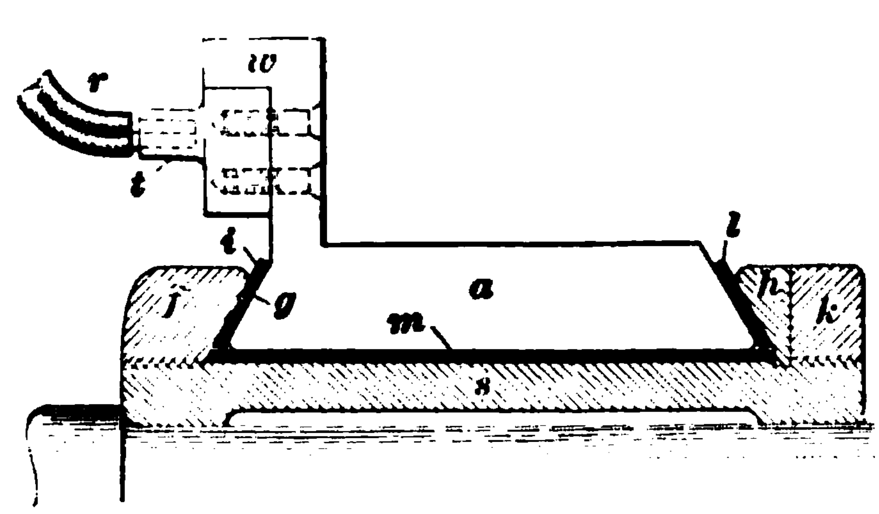


FIG. 36

then the mica sleeve *m*, the copper segments and the mica

insulating segments, the mica cone *l*, the wedge ring *h*, and finally the nut *k* is screwed up, clamping the whole firmly together. It is necessary that the commutator be very carefully made in order that it may successfully stand the strains of machining it and be perfect electrically. To this end the segments are very carefully tapered from the outer to the inner edge, to within less than $\frac{1}{1000}$ inch of the correct size, and the mica segments are calipered and made to a similar degree of accuracy. Shellac is liberally used in putting the commutator together, and after it is clamped, it is usually heated and screwed as tight as possible, cooled, and again tightened. On account of the very severe strains of tightening, the shell is subjected to very heavy strains and must therefore be of ample strength. If the shell is of iron, it may also be subjected to very severe strains on account of the copper bars expanding more than the iron shell when heated. Bronze is used for the shells of small commutators and cast steel or malleable iron for moderate-sized ones. If the wedging strains are taken by bolts, the shells may be of cast iron, especially in the larger sizes, where the tightening strains are not proportionally as large as in the smaller commutators. Note the method of connecting the conductors to the segment: The leads *r* from the two coils are first soldered firmly into the terminal *t*, which in turn is attached to the neck of the segment *w* by the two screws. In Fig. 37, the segment has but a very short neck, in which is milled a slot just wide enough for the conductors *r*, which are directly soldered in, thus avoiding the extra terminals of Fig. 36. This is a better and more common method of attaching the leads.

FIG. 37

81. The style of segment shown in Fig. 37 is quite satisfactory and is largely used. The diameter of the face, or working surface, is much greater than that of Fig. 36, as both the tightening bolts and clamping rings are beneath the surface of the face. This larger diameter is, of course, much more expensive in material and labor, but it is necessitated by the use of carbon brushes and multipolar types of field, as against metal brushes and bipolar fields. Metal brushes have low resistance, and therefore are small, while the heat developed in the face of the commutator due to both I^2R loss and to friction of the brushes is small, so that a commutator with a small surface for dissipating the heat is satisfactory. On the other hand, carbon brushes are of high resistance, a property useful in keeping down sparking, and must therefore be large, so the friction and I^2R losses are greater and the area for radiation must be increased in order that the commutator may not overheat. As it is, the commutator is usually the hottest running part of a modern dynamo, for the heat there can do little harm aside from producing strains in the structure due to unequal expansion of the metals, unless the temperature rises to such a degree as to melt the solder used in attaching the leads from the coils. The rise of temperature of a commutator is often limited to 55° C. above that of the surrounding atmosphere.

82. Multipolar designs require a larger diameter of commutator than bipolar designs, because they require more segments in proportion to the number of poles. It has been shown that, from one neutral point on the commutator to the next, there exists the full difference of potential of the generator, and the average number of volts per segment cannot be greater than a certain limited quantity. The mica between the segments cannot be safely made less than from .02 inch to .025 inch thick without causing trouble; and further, it has been found that a commutator with more than from 12 to 15 per cent. mica in its make-up will not wear well, and is therefore undesirable. Thus, if we limit ourselves to .025 inch mica as the thinnest insulation and

12 per cent. as the greatest amount of mica, then each segment and mica must be not less than $\frac{.025}{.12} = .2$ inch. This is not a bad limit to keep within; and for high voltages, small-sized multipolar generators will usually call for a fairly large diameter of commutator.

83. The segment *a*, Fig. 37, is clamped between the shell *s* and the wedge ring *h*, the two being clamped together by the bolts *b*. This construction, by putting the clamps below the surface, at once increases the diameter and shortens the length. For voltages of 250 or over, the mica cones *i*, *l* are preferably made longer than the segments, and a layer of string is carefully wound over the projecting part to protect it, as shown. This is done in order to keep the current from arcing over to the frame and thus grounding the machine.

84. Fig. 38 is a type of commutator suitable for large generators. The segments have a very long neck to make up for the difference in the diameters of the armature and commutator, the armature conductors here being too large to bend down to the segment. The commutator consists of a spider *b* with a hub, not shown; two clamping rings *c*, *c*, made in segments, and held in place by the bolts *f*; and two wedging rings *d*, made in segments. It will be seen that if the tap bolts *e* are tightened, *d* will be drawn up, wedging the clamps *c* inwards and thus clamping

FIG. 38

the commutator segments a. The rings c must evidently be made in segments. It is claimed for such a construction that defective copper segments may be replaced by removing

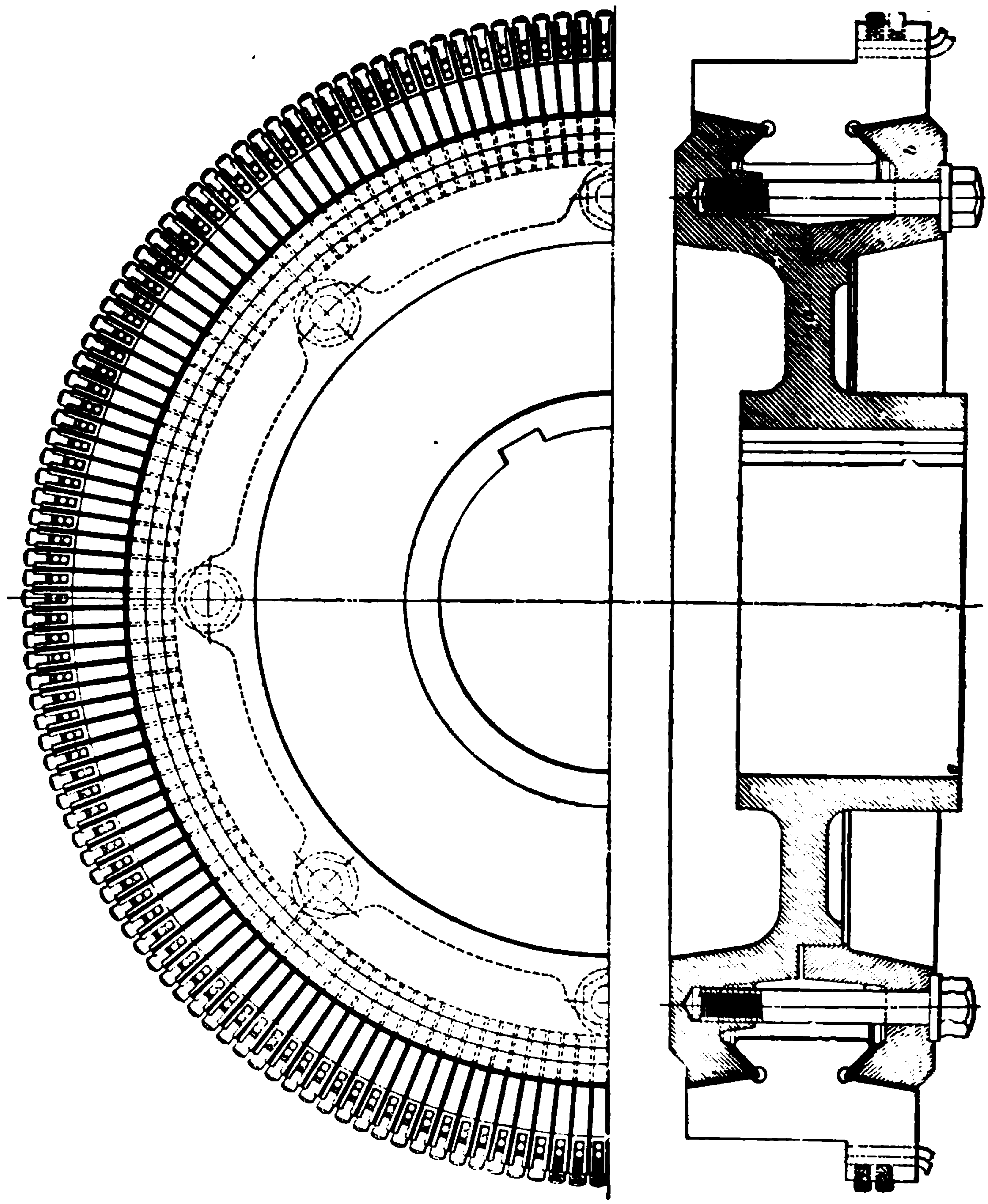


Fig. 30

only the segment of c, under which the defective part is held. Such a commutator has a very good property of

permitting air to circulate through its interior, thus assisting in cooling it; but it will be noticed that the heat is all developed in the copper segments that are separated by the mica from the spider, and mica is a fair heat insulator as well as electric insulator. Another good quality of this design is that the clamps *c*, *c* need not be tightly drawn together to hold the segments, as in Figs. 36 and 37, so the expansion and contraction of the copper segments can be permitted.

85. A completed commutator, of the type used with the armature shown in Fig. 27, is shown in Fig. 39. It is very similar in style to that shown in Fig 37, its peculiarities being the use of tap bolts instead of through clamping bolts, and also the use of setscrews in the segments for binding the conductors. The outside appearance is improved by the use of tap bolts, but they are generally more expensive than through bolts.

Fig. 40 shows a perspective and a half section of a commutator of a railway motor. It is a slight modification of Fig. 37, in that its diameter is not great enough to permit bolts being used beneath the segments, so a special nut *e* is used, which is screwed upon the shell by a spanner fitting into the holes shown, a setscrew being used to prevent its loosening; *f* is the bar, *b*, *b* the mica insulating cones, *a* the shell, and *d* the clamping ring.

Fig. 40

ARMATURE LOSSES AND HEATING

86. Since the output of a dynamo is limited by the temperature rise of its various parts, it is important that the heating be carefully considered in designing. The temperature rise depends on two factors, the rate at which heat is developed within the body and the ability of the body to dissipate the heat. The former quantity, usually termed the **losses,** may be computed with reasonable accuracy, but the latter is usually best determined by experience.

87. Division of Losses.—The losses in an armature may be divided into first the copper losses, which occur within the conductors due to their resistance; and second the iron losses, namely those due to hysteresis and to eddy currents in the armature core. Since the numerical value of the watts lost in a conductor due to its resistance is the product of the square of the current in amperes and the resistance of the conductor in ohms, the loss is commonly spoken of as the $I^2 R$ loss. This is frequently referred to as the $C^2 R$ loss, since the letter C was formerly used to denote current.

88. Estimation of Armature Resistance.—To compute the $I^2 R$ loss of a given armature, since its current output is known, it is merely necessary to determine its resistance in ohms. To measure the resistance of the windings of an armature of any size is a matter of considerable difficulty, because the resistance of the armature itself is usually so small that the resistance of the terminals is quite a large part of the total, and it is difficult to eliminate this from the measurements. Consider for instance a parallel or multicircuit winding for a multipolar generator. To obtain the resistance of all paths in parallel, since they cannot be individually measured in a winding completely connected up, they must be connected together as they are when in operation, and these connections involve the brushes, brush-holders, and their connecting wires. However, it is not often necessary to measure the resistance of such a winding, as reliable results can be obtained from calculations.

Obviously the number of circular mils area of a round wire is obtained by squaring its diameter in mils.

It has already been shown that the resistance in ohms of any copper wire of uniform cross-section at ordinary temperatures may be computed from the formula

$$R = \frac{10.8 \times \text{length in feet}}{\text{area in circular mils}} \qquad (13)$$

In dynamo calculations the resistance of a mil foot of wire will be considerably above 10.8 ohms, because the wire is warm when the machine is in operation. A fair value for the resistance of a mil foot under these conditions is 12 ohms; thus,

$$\text{warm resistance } R = \frac{12 \times \text{length in feet}}{\text{area in circular mils}} \qquad (14)$$

and since there are 12 inches in a foot, this may be written

$$R = \frac{\text{length in inches}}{\text{area in circular mils}} \qquad (15)$$

89. To compute the resistance of an armature coil, it is necessary, first, to estimate its length and the area of the section of copper. If the copper conductors are of rectangular section, the area in square mils may be obtained by multiplying together the two dimensions of the wire in thousandths of an inch. A circular mil has a smaller area than a square mil by the ratio of the area of a circle to that of a square, or by .7854; so that if the area of a conductor in square mils is divided by .7854, the result will be the area in circular mils.

Let r_c be the resistance of a single armature coil calculated, say, from formula **15,** and let C be the number of coils on the armature connected up into a winding having m paths, or circuits. Then the resistance of a single path, since there will be $\frac{C}{m}$ coils in series per path, is $\frac{r_c C}{m}$. But there are m such paths in parallel in the complete armature winding, so the total resistance will be only $\frac{1}{m}$ of that of one path, or

$$R_a = \frac{r_c \times C}{m^2} \qquad (16)$$

TABLE II

MAGNET WIRE, BROWN & SHARPE GAUGE

Gauge Number	Diameter in Mils				Area Circular Mils	Ohms Per 1,000 Feet at 20° C. 68° F.	Pounds Per 1,000 Feet Bare
	Bare	Single Cotton-Covered	Double Cotton-Covered	Triple Cotton-Covered			
0000	460.0			478	211,600	.049	640.50
000	409.6			428	167,805	.062	508 00
00	364.8			383	133,079	.078	402.80
0	324.9			343	105,534	.098	319.50
1	289.3			307	83,694	.124	253.30
2	257.6			276	66,373	.156	200.90
3	229.4			247	52,634	.197	159.30
4	204.3		216	220	41,742	.248	126.40
5	181.9		194	198	33,102	.313	100.20
6	162.0		174	178	26,250	.394	79.46
7	144.3		156	160	20,816	.497	63.02
8	128.5		140	144	16,509	.627	49.98
9	114.4		126	130	13,094	.791	39.63
10	101.9	108.0	112	116	10,381	1.000	31.43
11	90.7	97.0	101	105	8,234	1.257	24.93
12	80.8	87.0	91	95	6,529	1.586	19.77
13	72.0	78.0	82	86	5,178	1.999	15.68
14	64.1	71.0	75	79	4,107	2.521	12.43
15	57 1	63.0	67	71	3,257	3.179	9.86
16	50.8	55.0	59	63	2,583	4.009	7.82
17	45.2	49.0	53	57	2,048	5.055	6.20
18	40.3	44.0	48	52	1,624	6.374	4.92
19	35.9	39.0	43	47	1,288	8.038	3.90
20	32.0	36.0	40	44	1,022	10.140	3.09
21	28.5	32.0	36	40	810	12.780	2.45
22	25.3	29.0	33	37	642	16.120	1.94
23	22.6	27.0	31	35	509	20.320	1.54
24	20.1	24.0	28	32	404	25.630	1.22
25	17.9	22.0	26	30	320	32.310	.97
26	15.9	20.0	24		254	40.750	.77
27	14.2	18.0	22		202	51.380	.61
28	12.6	17.0	21		160	64.790	48
29	11 3	15.0	19		127	81.700	.38
30	10.0	14.0	18		100	103.000	.30
31	8.9	12.5			80	129.900	.24
32	8.0	11.5			63	163.800	.19
33	7.1	10.5			50	206.600	.15

An example of the use of this formula will be given later, in connection with the design of a dynamo.

90. In Table II is given the properties of copper wire in sizes corresponding to those of the American or Brown & Sharpe gauge. This table gives in successive columns the gauge number; the diameter in mils of the wire when bare, single cotton-covered, double cotton-covered, and triple cotton-covered; the area in circular mils; the resistance in ohms per 1,000 feet; and the weight in pounds per 1,000 feet. The omission of a size in the columns for the insulated diameters indicates that the size in question is not ordinarily insulated in that manner. Thus, larger wire than No. 10 B. & S. is not ordinarily single cotton-covered, nor are smaller sizes than No. 25 triple cotton-covered, etc.

91. In armatures, double and triple cotton-covered wires are chiefly used, although for very small wire, say, above 25 B. & S., double silk or single cotton is preferred by some manufacturers, since double-cotton insulation occupies an excessive amount of room. Single insulation is not desirable, unless the wire will have very little handling, for the covering may slip along the wire and leave a portion entirely bare. This is not liable to occur with double or triple coverings, since the direction of winding the insulation is different in the two layers.

92. Estimation of Hysteresis Loss.—The loss in the armature core, due to hysteresis, depends on the volume of the iron, the magnetic density, the frequency of the magnetic reversals, and the quality of the iron; that is to say, each magnetic cycle requires a certain expenditure of energy per cubic inch, and two cycles will require twice as much as one. A *magnetic cycle* in a direct-current dynamo is accomplished when the armature revolves through the angle of two poles; thus, in a bipolar there is one cycle per revolution, in a four-pole machine there are two per revolution, etc. The *frequency* is the number of complete cycles per second; numerically, it is the product of the number of pairs of poles and the revolutions per second. If a core of V cubic inches is

subjected to a frequency of n cycles per second, and if at the particular magnetic density there is a loss of a watts per cubic inch and per cycle, the total loss due to hysteresis is

$$W_h = a \times V \times n \qquad (17)$$

93. Table III shows the loss in watts per cubic inch per cycle for an average quality of annealed iron, such as is ordinarily used for armatures, and is here given for convenient reference in connection with the subject of dynamo design. Iron of very much poorer quality, that is, having a larger value for a, is undesirable, as the iron losses may so overheat the core as to decrease the capacity of the machine. For transformers and for generators with high frequencies, it is necessary that the value of a be as low as possible, and is usually about half of that given in the table.

TABLE III

WATTS LOST PER CUBIC INCH PER CYCLE PER SECOND

Density. Lines Per Square Inch	a = Watts Per Cubic Inch. 1 Cycle Per Second	Density. Lines Per Square Inch	a = Watts Per Cubic Inch. 1 Cycle Per Second
30,000	.0042	90,000	.0244
40,000	.0067	95,000	.0267
50,000	.0095	100,000	.0289
60,000	.0128	105,000	.0312
65,000	.0145	110,000	.0337
70,000	.0164	115,000	.0362
75,000	.0183	120,000	.0387
80,000	.0202	125,000	.0414
85,000	.0223		

94. Eddy-Current Loss.—The eddy-current losses are most difficult to compute, and, in fact, are practically impossible to predetermine with accuracy. This is especially the case if the slots are filed or milled after the armature punchings have been assembled; such treatment connects the disks

together and may greatly increase the eddy-current loss. Fortunately, they are usually of minor importance, and may be estimated with sufficient accuracy. A very good way is to assume the eddy-current loss to be proportional to the hysteresis loss, which it very nearly is, and so increase the value computed for the latter by from 25 to 100 per cent. This will usually be found to be quite satisfactory unless other data is at hand on the subject. A very good rule is to allow 75 per cent. over the values given by the table, for both hysteresis and eddy currents combined. This will usually be found to be very safe, but should, of course, be checked by tests with the first machine built, and the rule modified to suit the action of the type of dynamo in question.

95. Radiating Surface and Temperature Rise.—The sum of the I^2R and the hysteresis and eddy-current losses gives the total watts that must be radiated from the armature surface (exclusive of the commutator); if the total number of square inches of radiating surface is computed, the ratio of watts to the radiating surface gives the watts lost per square inch. By noting the number of watts that must be radiated per square inch, an idea can be formed as to the probable temperature rise.

While it would seem as though these calculations should be simple enough, there are many ways of estimating the losses and also the radiating surface. One way is to estimate the total area of the armature, including the ends, and, if the core is ring-shaped, the inside cylindrical surface. Another way is to include only so much of the I^2R loss as occurs in the slots, adding this to the iron loss, and taking for the radiating surface only the outside cylindrical surface of the armature core, omitting the area of the end connections. Any method will, of course, give satisfactory results, if it is obtained from tests of actual machines of approximately the same type as those for which the heating calculations are required.

96. It is customary to limit the temperature rise of the armature to from 40° to 45° C. above that of the surrounding

atmosphere. From numerous tests of drum-wound multipolar armatures with both barrel and spiral-end connections, the following table of watts that can be radiated per square inch of armature core surface without the temperature rise exceeding 45° has been prepared. The calculations were made according to the second method just given.

TABLE IV

Peripheral Velocity of Armature Core. Feet Per Minute	Watts Loss Per Square Inch of Surface of Armature Core for a Rise of 45° C.	
	Good Ventilation	Poor Ventilation
2,000	2.4	1.75
3,000	3.5	2.40
4,000	4.5	2.80
5,000	5.4	3.10

By good ventilation is meant a ventilating duct in the armature core for about every 3 inches of length parallel to the shaft. These air ducts should preferably be wider than ¼ inch to prevent their becoming clogged up with dust. By poor ventilation is meant narrow air ducts or none at all, windings covered by canvas or other material, or frames so shaped as to obstruct the free circulation of air.

In the design of a dynamo to be given later, an example of the heating calculations is given. In designing, the computed watts lost per square inch of the armature-core surface should not exceed the value given in the table, because the machine would then probably not be capable of delivering its output continuously without overheating. Nor should the computed value be less than .8 of that in the table, since this would indicate that the design is too large to be economical of material, and should be made smaller by increasing the densities until the estimated temperature rise comes within the limits given.

97. Heating calculations are perhaps the most unsatisfactory of any of those concerning dynamos. The iron of the armature core is liable to vary greatly in quality, and tests usually show very discordant results in samples taken from the same lot of iron. Again, the radiating qualities of a surface are somewhat uncertain, for a coat of varnish or a film of oil may make a difference of from 20 to 30 per cent. The foregoing rules must be taken, therefore, only as giving very approximate values, and data on such subjects as heating and sparking must be collected for reference by each electrical designer for himself, from the factory tests of the generators as they are built.

DESIGN OF THE FIELD MAGNET

98. The field-magnet frame is designed especially to carry or conduct the magnetic flux from pole to pole. It must also be provided with the exciting coils, properly insulated and protected, and designed so as to set up the required magnetic flux when currents are passed through them. The materials of which the field magnet is made are selected, usually, from considerations of economy, from one or more of the following metals: Cast iron, low-carbon cast steel, wrought-iron forgings, or sheet-iron or steel punchings. The magnetic properties of these substances are shown in the curves, Fig. 41. These curves give the ampere-turns per inch of length of magnetic circuit for different values of the density. Now, it has already been shown that

$$\mathbf{H} = \frac{3.192 \times \text{ampere-turns}}{\text{length of magnetic circuit in inches}}$$

which may be written

$$\frac{I\,T}{l} = \frac{\mathbf{H}}{3.192} = \mathbf{H} \times .313 \qquad \textbf{(18)}$$

$\frac{I\,T}{l}$ is the ampere-turns divided by the length of the magnetic path in inches; hence, it is the ampere-turns

per inch, and the value of this quantity is found by dividing the value of **H** by 3.192, or multiplying it by .313.

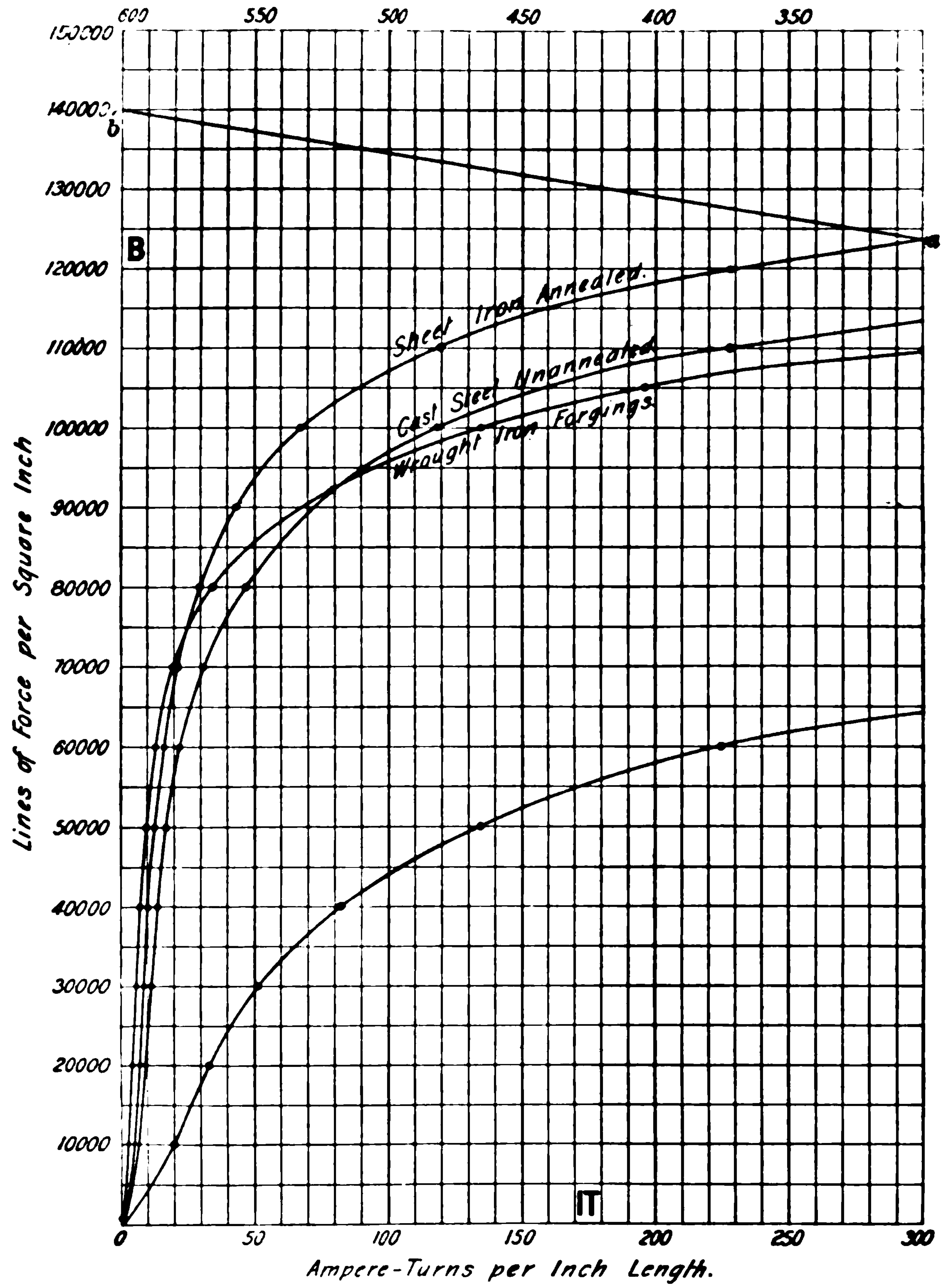


FIG. 41

99. From the curves, it is seen that cast iron is scarcely half as good as the others magnetically, but its cheapness in comparison and also its ability to be readily molded into

any intricate shape sometimes outweighs its magnetic shortcomings. Wrought-iron forgings are too expensive, unless of very simple shape, as, for instance, a straight, square, or round piece that may be cut from a long bar rolled for the purpose. Sometimes, on very small machines, drop forgings of wrought iron or wrought steel are used. Steel castings are very largely used, for they are comparatively cheaper than iron castings, since they are twice as good magnetically, although costing more per pound. Steel is cast at very high temperatures and intricate shapes are molded with more difficulty than with iron; also the shrinkage is much greater and the liability to form blowholes and shrink holes is greater on account of the higher temperatures of pouring. Where lightness is desired, as, for example, in the frames of railway motors, steel castings are used almost exclusively.

100. Punchings made from the iron or steel sheets may be readily assembled and riveted together into parts with rectangular sections with comparative economy, if the parts are small, for they do not require machining after being accurately punched; the saving in this way over castings helps to make up for the labor of building them up. Where the magnetic flux does not vary rapidly through a part made up of laminations, as in the magnet frame of a dynamo, the laminations may be riveted together; but this construction would be undesirable for an armature on account of the eddy currents through the rivets. Modern generators frequently have pole pieces of laminated iron to prevent pole-face eddy currents.

MAGNETIC DENSITIES IN VARIOUS PARTS

101. Armature Core.—The **magnetic densities** used in the materials in modern dynamos depend not only on the material but also on the parts of the magnetic circuit for which it is to be used. The armature core is subject to hysteresis and eddy-current losses, which increase with the density, and therefore usually limit the density to such a

point that the losses will not be so great as to overheat the armature and lower its output. The density here is usually between 50,000 and 100,000 lines per square inch, the lower values being for machines in which the frequency of magnetic reversals is high and the higher values for those in which the frequency is low.

102. Armature Teeth.—In the teeth, the magnetic density should be quite high, say from 120,000 to 130,000 lines per square inch, as a high density here means a high reluctance, which will interfere beneficially with the cross-magnetizing action of the armature.

103. Pole Pieces and Magnet Cores.—In the **pole pieces**, the density will generally be low, since the air-gap density is usually between 30,000 and 70,000 lines. It is, however, best to run the density of the magnet cores well up to the saturation for two reasons. In the first place, some part of the magnetic circuit should be saturated, since the machine will otherwise be unstable in its action. A small change in the ampere-turns will mean a comparatively large change in the flux and E. M. F., and it is best that the magnetic cores, rather than any other parts except the teeth, be saturated. Secondly, if the area and perimeter of the magnet cores are made small, the weight of the copper in the exciting coils will be decreased. If the magnet cores are of cast iron, the density should be from 40,000 to 50,000 lines; while if of steel, laminated, or wrought iron, from 95,000 to 105,000 is best. Cast iron is now seldom used for magnet cores of direct-current machines.

104. Yoke.—The density in the yoke is usually not made very high, unless the type of frame is such that the path for the magnetism through the yoke is short. For cast-iron yokes, from 30,000 to 40,000 lines per square inch is used; while for steel and wrought-iron, the density should be 70,000 to 90,000. Cast iron is very largely used for yokes on account of the ease of molding; besides, a fairly large cross-section of metal in the yoke is often desirable in order

to give mechanical stiffness. With cast-steel yokes the cross-section necessary to carry the flux is sometimes not great enough to give mechanical stiffness. This point will be illustrated later on in connection with the design of a machine.

GENERAL FEATURES RELATING TO MAGNET FRAMES

105. The curves given in Fig. 41 are not to be considered as absolute, for it is not infrequent to find materials whose properties differ by 10 per cent. or more from those given, especially in the case of steel castings. The composition of the irons and their treatment have much to do with their magnetic qualities. In general, the purer the steel or wrought iron and the softer it is, the higher will be its magnetic permeability. Chilling lowers the permeability and annealing raises it; also, impurities, such as carbon, that tend to harden the metal, usually lower the permeability, while those that tend to soften the metal raise its permeability when present in small quantities.

Magnet frames are frequently constructed of more than one substance, for it is often desirable or necessary to have one part—such as the pole pieces—removable from the rest, so that the use of a different material involves no difficulties. Even where the parts are not required to be detachable, there may be one part, say of wrought iron or punchings, cast into another. Wrought-iron or laminated pole pieces are frequently cast into the yoke.

106. The selection of the proper type of magnetic frame for a certain purpose is by no means a simple one, and the choice must be guided largely by experience. If the machine is not restricted, some type giving large radiating surfaces for the armature and field coils should be taken in order that the temperature rise from the losses shall not be excessive. If the machine is to be entirely or partially enclosed, the type of frame must be such as will readily lend itself to

enclosing the parts of the machine. In street-railway motors, the casing is the magnet frame itself, which is of cast steel. Sometimes small bipolar machines are provided with covers made of brass, or some other non-magnetic metal; but in larger machines it is possible to select a multipolar type of such form that the casing does not form a path or circuit for magnetic leakage, so that it may be made of cast iron.

107. Magnetic Leakage.—Having selected the type of magnet frame and the material, or materials, of which it is to be made, it is a very simple matter to determine the areas of the various sections by dividing the total flux that must pass through the part by the permissible magnetic density for the material. In determining the flux, it is necessary to take account of magnetic leakage. The magnetic leakage is not easily determined, but accuracy in this case is not necessary, since the magnetic properties of the material vary so greatly that a considerable margin must be allowed anyway. The flux entering or leaving the armature under a pole is readily computed from formula **1**, solved for Φ, and is a perfectly definite quantity.

For purposes of calculation this flux is usually increased by a factor, called the **coefficient of magnetic leakage,** in order to obtain the flux in the pole pieces and yokes. The flux calculated from the formula is often termed the **armature flux,** while that which is increased by including the leakage factor is called the **field flux.** The armature flux is used in the calculations of the densities in the air gap, the teeth, and in the armature core; the field flux is used in the calculations of the densities in the pole pieces, magnet cores, and yoke. Of course, the actual flux passing various points does not suddenly increase on account of leakage at the pole piece, but leakage increases it gradually as we pass up the pole pieces and magnet cores toward the yoke. However, to make the calculations simple this assumption is made, and in practice it is found that the results obtained from so doing are entirely satisfactory in most cases.

108. It is impossible to prevent magnetic leakage, and to compensate for it, it is only necessary to increase the sectional area of the field-magnet frame; so that where the leakage flux is only 10 or 20 per cent. of the useful armature flux, it is not a serious matter, but designs in which there is a leakage of from 25 to 50 per cent., or more, should be avoided, as the increase in weight of a corresponding amount for the magnet would involve an undesirable expense.

The leakage coefficient is taken as unity plus the per cent. of leakage; thus a leakage coefficient of 1.2 means that the leakage flux is 20 per cent. or .2 of the armature flux. It has been found by experiment that the value of the leakage coefficient does not vary greatly with the size of the machine, but it is practically constant for a given type, although it is somewhat smaller for the larger sizes.

DETERMINATION OF AMPERE-TURNS ON FIELD

109. As has already been stated, there must be a complete magnetic circuit provided for the magnetic lines, and in most types of field magnets there are several complete circuits, each one of which has linked with it, after the manner of Fig. 42, a field coil whose ampere-turns serve to set up the magnetic flux. In order to determine the proper strength of the field coil, or coils, in a particular circuit, it is first necessary to map out the path of the magnetic lines through the circuit. To determine the length of the path for purposes of calculation, it is necessary to determine the mean path, or the average between the shortest and longest paths. In the diagrams of field magnets shown in Figs. 31 to 40, Part 1, the mean paths of the magnetic flux are shown by the dotted lines.

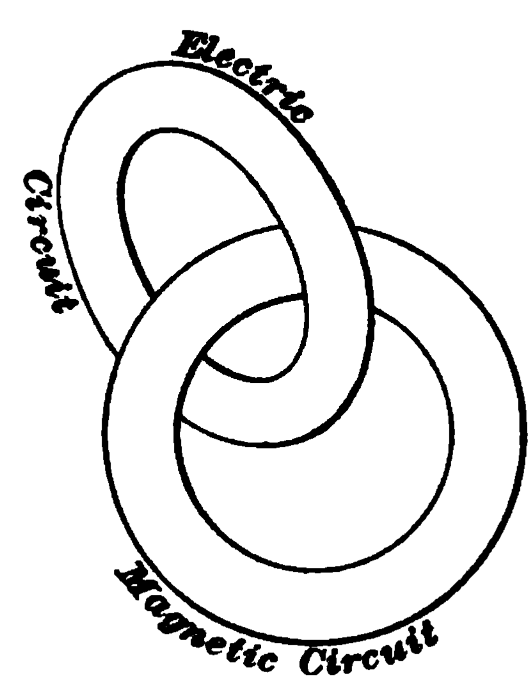


FIG. 42

110. Having computed the armature flux per pole from formula **1**, and the field flux per pole by multiplying this by the leakage coefficient, the densities in the various parts may be determined if the areas of the sections are known, taking care to note and allow for the division of the flux, if any. Or, if the density in the various parts has been decided on, the area of any section is evidently the quotient of the flux through it divided by the density. Knowing the densities, the ampere-turns required per inch of length of path may be determined from the curves, Fig. 41, for magnetic materials; while for the air gaps, the ampere-turns are computed from the formula

$$IT = \frac{\mathbf{B}_g \times l}{3.192} = \mathbf{B}_g \times l \times .313, \qquad \textbf{(19)}$$

where $\mathbf{B}_g$ = magnetic density in lines per square inch;
l = length of path through air in inches;
IT = ampere-turns required.

The total ampere-turns for the magnetic circuit in question are now found by obtaining the product of the ampere-turns per inch by the length in inches of the mean path for each part of the circuit and then taking the sum of these products. An example of these calculations is given later with the design of a machine.

FIELD WINDINGS

111. Having determined the number of ampere-turns required on a magnetic circuit, the number of turns is next to be calculated. Referring to the diagram of the magnetic circuit of the particular type of magnet frame under consideration, note the number of coils thereon, and if each is to be of the same strength, divide the total number of ampere-turns required by the number of coils on a single magnetic circuit; the quotient gives the number of ampere-turns per coil. In the radial-pole type, Fig. 40, Part 1, it will be noticed that there are two magnetic circuits threading through each coil, and that each magnetic circuit threads

through, or links, with two coils. In this case there are two coils per magnetic circuit, and the fact that each coil surrounds two different circuits does not affect the calculations in any way, except that the magnet cores must be twice as heavy to conduct the flux of both circuits through the coil.

112. Determination of Series-Field Winding. — If the field coil is series-wound, the number of turns the coil should have is obviously the quotient of the number of ampere-turns required divided by the number of amperes developed at full load. The wire must have sufficient cross-section to safely carry the current without overheating. It has been found that the surface of a coil can radiate from ½ to ¾ watt per square inch of outside area, with a rise in temperature of about 40° C. To determine the proper size of wire for a series-wound coil, it is necessary to estimate the radiating area of the coil in square inches and take one-half or three-fourths of this as the permissible loss in watts W that can be safely dissipated. If I is the current in amperes in the coil and R is its resistance in ohms, then $W = I^2 R$, or $R = \frac{W}{I^2}$. But, from formula **15**,

$$R = \frac{\text{length in inches}}{\text{circular mils}} = \frac{W}{I^2}$$

Calling L the average length of a turn of wire and T the number of turns, then the total length in inches of the coil is $L \times T$, and if q is the area of the wire in circular mils,

$$R = \frac{L\,T}{q} = \frac{W}{I^2},$$

whence

$$q = \frac{L\,T\,I^2}{W} \tag{20}$$

Formula **20** may be written $q = \frac{L \times I\,T \times I}{W}$. But $I\,T$ is the number of ampere-turns, so that we may write

$$q = \frac{\text{mean length of a turn in inches} \times \text{ampere-turns per coil} \times \text{current}}{\text{watts dissipated per coil}} \tag{21}$$

However, the form given in formula **20** is as useful as any.

113. Determination of Shunt Winding.—If the field coil is shunt-wound, the size of wire is usually determined first, and the number of turns later in the following manner. Let e be the E. M. F. impressed at the terminals of a single shunt coil, then the shunt current i will be equal to $\frac{e}{R}$, whence the ampere-turns $i\,T = \frac{e}{R} \times T$, but $R = \frac{L\,T}{q}$, which, substituted in the above, gives

$$i\,T = \frac{T \times e \times q}{T \times L} = \frac{e \times q}{L}$$

This may be written

$$q = \frac{i\,T \times L}{e} \qquad \textbf{(22)}$$

From formula **22** it will be noticed that the circular-mils area of a shunt wire is independent of the number of turns, the resistance of the coil, and the current flowing in it, for these qualities are not involved in the calculations. That is, the size of wire depends on the ampere-turns and not on the values of the current or turns taken separately. That this is so can be readily seen from an example. Suppose that a coil is subjected to a pressure of 25 volts, and that 10 amperes flows through, say, 300 turns, setting up 3,000 ampere-turns. If half the turns were removed, the resistance would be halved; consequently, with the same E. M. F. at the terminals, the current would be increased to 20 amperes. The ampere-turns are $i\,T = 20 \times 150 = 3{,}000$, which is the same as before. Notice that in decreasing the number of turns the current is increased; this increases the number of watts lost in the coil and the heating of a shunt-wound coil therefore depends on the number of turns of wire.

To determine the number of turns of wire for a shunt coil, estimate the radiating area of the coil and determine how

many watts W it can safely dissipate. The allowable current in the coil then is $i = \frac{W}{e}$ and the correct number of turns is

$$T = \frac{i\,T}{i} = \frac{i\,T \times e}{W} \qquad (23)$$

114. Comparing the methods of calculating shunt-windings and series-windings, it will be noticed that in series-coils the number of turns follows from the current and the ampere-turns, while the size of wire is determined from heating considerations. In shunt coils, the size of wire is determined by the ampere-turns, the mean length of a turn, and the E. M. F. impressed on the terminals, while the number of turns of wire is determined by the heating.

115. Since the field coils surround parts of the magnet frame usually termed the **magnet cores,** it is evidently desirable that the cores have as small a perimeter as possible, so that the mean length of a field turn may be short, and thus the weight of field copper kept down, as the cost of this is quite a large item in the cost of a dynamo. The magnet cores must have sufficient area to carry the flux, and as the area required is much less for wrought iron, cast steel, or laminated iron or steel than for cast iron, magnet cores are rarely made of cast iron. Further, for a given area, a circle has the smallest perimeter of any figure; and of rectangular figures, the square has the least perimeter. Therefore, magnet cores are preferably made cylindrical, except in the case where laminated iron is used, when it becomes difficult to make the section other than rectangular, and in this case the square is preferable. Where the departure from a circle or square is small, as in the case of an ellipse or a rectangle whose major and minor axes or sides do not differ greatly in length, the weight of copper required is not greatly affected; but designs where the major axis of an ellipse, say, is two or more times the minor should be avoided. The relation between the perimeters for the same areas in any cases may be readily computed from geometry. As an example, let it be required to compare a square and a circular

section. If we take the area of a circle 1 inch in diameter as a basis for comparison, then the perimeter or circumference is 3.1416 inches. The area is $\frac{3.1416}{4} \times d^2 = .7854$ square inch. A square whose area is .7854 inch has a side $\sqrt{.7854}$ inch long $= .8862$ inch; therefore, its perimeter is $4 \times .8862$ inch $= 3.5448$ inches, so that the ratio of the two perimeters is $\frac{3.5448}{3.1416}$, or 1.13; in words, a square has a perimeter 13 per cent. longer than a circle enclosing the same area.

116. It will be noticed that formula **22**, for the area of a shunt-field wire, involves the mean length of a turn, and if the perimeter is increased, the size of wire must be increased; as the length of wire is thereby increased, the weight of wire is doubly increased by increasing the mean length of a turn, other things remaining constant. It might be stated that for the same number of watts lost in two shunt coils developing the same number of ampere-turns, at the same terminal E. M. F., the weights of copper required varies as the square of the mean length of a turn. If the weight of wire required for the coils wound around a core of circular section, then, is 1, the weight required for the coils to surround a core of square section would be $(1.13)^2 = 1.277$, or 27.7 per cent. more. In this case, the difference in cost of the coils will be even more than this comparison would indicate, since the difficulty of winding a square coil increases the labor cost quite considerably.

117. Space does not here permit a complete study of all the various types of field magnets and field-magnet windings that may be used, but the subject, fortunately, is one that can readily be studied from an inspection of machines, and also from the illustrated publications of manufacturers. The same is true of other parts, such as the designs of pedestals, bedplates, rails, rocker-arms, brush holders, terminal boards, etc., and the student is urged to make such study of the construction of generators as his opportunity and time may permit.

DYNAMOS AND DYNAMO DESIGN

(PART 3)

DESIGN OF A 100-KILOWATT DYNAMO

DESIGN OF ARMATURE CORE AND WINDING

1. For the purpose of illustrating the principles of design, let it be required to work out a 100-kilowatt belt-driven dynamo. Armature windings are to be calculated for the three customary voltages, viz., 125, 250, and 500 volts, when the dynamo is running at a moderate speed, say between 500 and 600 revolutions per minute.

2. Estimation of Total Output.—We have the equation

$$\text{watts} = \frac{\frac{2}{3}\pi^2 D^2 L \mathbf{B}_g K S}{10^8 \times 60} \qquad (1)$$

The watts in this equation are not the commercial watts output or the output at the machine terminals, but the total electrical output of the armature, which latter includes the electrical losses in addition to the commercial output. The electrical losses are but a small percentage of the total watts and may be neglected in preliminary calculations on sizes over 50 kilowatts, but in very small machines they would not be negligible. The percentage of electrical loss is, further, somewhat higher for the lower voltages.

The electrical efficiency U_e has been defined as the ratio of the net electrical output W to the total electrical output W_t, or

$$U_e = \frac{W}{W_t} = \frac{\text{net electrical output}}{\text{net electrical output} + \text{electrical losses}}$$

This ma·· be written

$$W_t = \frac{W}{U_e}$$

Then, the total electrical output that is required from the armature under consideration is $\frac{100{,}000}{U_e}$ watts.

3. The approximate values given in Table I may be taken for the value of U_e for moderate-speed generators.

TABLE I

ELECTRICAL EFFICIENCIES OF DYNAMOS

Output Kilowatts	Electrical Efficiency	Output Kilowatts	Electrical Efficiency
.1	.75	30	.930
.5	.80	50	.950
1.0	.85	100	.960
3.0	.87	300	.970
5.0	.89	500	.975
10.0	.91		

4. It will be noted that formula **1** has the following unknown quantities:

$\%$ = percentage of armature surface covered by poles;
D = diameter of armature in inches;
L = length of armature in inches;
$\mathbf{B}_g$ = average magnetic density in the air gap;
K = number of ampere-conductors per inch of armature circumference;
S = speed of armature in revolutions per minute.

There are in all six unknown quantities and but a single equation determining the relation between them; it follows, therefore, that this equation can determine but one of the six, and the others must be determined in some other way, or assumed. The problem of designing a dynamo varies very much according to which of these quantities are known or assumed. Each one of the six will be considered separately, and the considerations ordinarily determining its value will be explained.

CONDITIONS GOVERNING PRELIMINARY ASSUMPTIONS

5. The **percentage of armature surface covered by poles** should be as large as possible, but some space must be left between the poles to provide a neutral region for commutation, as has already been explained. If the air-gap density is fixed, the greater the surface covered, the greater will be the total magnetic flux, and the output of the armature thereby increased; while with the total magnetic flux fixed, the greater the surface covered, the lower will be the magnetic density in the air gap and the less the number of ampere-turns required to maintain this density, so that the efficiency will be increased on account of the smaller magnetizing currents required to excite the fields. In any case, it is an advantage to have the percentage large. It usually is between 60 per cent. and 80 per cent., the former value for small sizes, or for those designs in which the field coils are slipped over the end of the pole pieces. For the present design .75 will be assumed as the value of the percentage.

6. The **diameter of the armature** is frequently the quantity that is determined by the equation. However, since it is involved to the second and sometimes to the third degree, the calculations are somewhat simplified if it is assumed or known. The diameter might well be determined in case the size of the machine is limited, as, for instance, in street-car motors. It is often desirable to make use of punchings from the center of larger armatures, and in this case, also, the diameter is limited. In designing a complete

line of machines, it is important that the sizes be properly related to one another, and it is best, therefore, to assume the various diameters to be used. For the problem under consideration, the diameter will be determined from the formula.

7. The **length of the armature core** is not usually made more than 15 inches or 18 inches for drum windings, unless the speed and magnetic densities are low, because the E. M. F. developed by a single turn consisting of two-face conductors then becomes as high as the number of volts allowable between commutator segments. The inductance of the coils also increases with the length of the core, and where the coils lie in slots and each conductor carries a large number of amperes, say over 100, it becomes extremely difficult to prevent inherent sparking at the commutator with armature cores 18 inches or more long. Where the magnet cores are near the pole pieces, as is usually the case, it is desirable that the length parallel to the shaft be so taken as to make the pole faces suitable for round or square magnet cores, as these are most economical of field copper. In such cases, the length of the armature is related to its diameter and the number of poles. Suppose, for example, that for round magnet cores, it is desirable that the pole faces shall be approximately square, or, in other words, that the length of the armature parallel to the shaft shall be about equal to the length of the arc of a pole. This may be expressed in a formula; thus,

$$L = \% \frac{\pi D}{p} \qquad (2)$$

where p is the number of poles and the other symbols have their usual significance. It is convenient to substitute for L in formula **1** the value $h D$, where h is the ratio of the length of the armature to its diameter. For square pole faces, then, from formula **2**,

$$h = \frac{L}{D} = \frac{\pi \times \%}{p}$$

When the pole pieces are made of laminated iron, having projecting horns, the arc should be longer than the length of the armature if the magnet cores are to be square. The amount by which it should be longer depends on the ratio of the magnetic densities in the air gap and magnet cores and on the magnetic leakage coefficient. A good rule in such cases is to take the length of the armature core .6 or .7 the length of the arc for laminated pole pieces. Let it be assumed for the design at hand that the length of the armature is .65 times the length of the polar arc, and that the number of poles is 6. The value of h then becomes

$$h = \frac{\pi \times \%}{p} \times .65 = \frac{3.1416 \times .75}{6} \times .65 = .255, \text{ say } \tfrac{1}{4}$$

That is, the length of the armature core parallel to the shaft will be $\frac{1}{4}$ the diameter of the core. This assumes that the design will have laminated poles.

8. The difference between machines with and without laminated poles is quite marked. If the poles are solid, the length of the air gap must be greater and the slot opening narrower in order to prevent pole-face eddy currents, as has been already explained. The slots in this case are usually made with overhanging teeth, or are straight but narrow and numerous. On the other hand, machines with laminated poles may have very short air gaps and large open slots with several coils in each. These wide slots reduce the inductance considerably and, hence, tend to improve commutation. But this is offset by the fact that since there are many coils per slot, the armature will turn a considerable angle during the commutation of the coils in a single slot; the coils, therefore, will commutate in different parts of the neutral region between the poles, and they may not all commutate equally well. This will result in the blackening or burning of one segment in the commutator for every slot. Such unequal sparking is very objectionable, since it causes the commutator to wear irregularly and become very rough.

9. Density in the Air Gap.—By density in the air gap is here meant the average magnetic density obtained by dividing the total armature flux per pole by the area of the armature core facing a pole. This quantity is usually taken as large as possible in order that the output of a machine may be large for its dimensions. It is limited by the magnetic saturation of the teeth and by the relation between the sizes of the slots and teeth. In order that the air-gap density may be high, the percentage of the circumference occupied by slots should be small, but in this case, obviously, the ampere conductors per inch of circumference must also be small, and the output is decreased on this account, while with a large percentage occupied by slots, the teeth become so thin that the flux they will carry, as well as the air-gap density, is decreased, and the output is again decreased. Between these two extremes there is a maximum that it is desirable to attain. The average air-gap density is usually between 40,000 and 60,000 lines per square inch, but may be anywhere from 25,000 to 75,000 lines. The lower values are usual for smaller machines, such as fan motors, and the higher values for very large dynamos, usually with laminated poles. By this latter construction, the size of the slots may be greatly increased, so that their number is reduced, as is also the room on the circumference occupied by slot insulation, and, consequently, a little larger percentage of the armature circumference is left for the teeth. At the same time, laminated poles permit the use of short air gaps, so that higher magnetic densities may be secured without the necessity of too great a number of ampere-turns on the field to set up the flux across the gaps. For the present design, an air-gap density of 55,000 lines per square inch will be assumed.

10. Ampere Conductors per Inch of Circumference. As has already been stated, this is restricted by the room in the slots. It has been found that the losses due to resistance of the armature conductors are objectionably large if the conductors have an area of less than from 500 to 600 circular mils per ampere of current flowing through them.

These losses, along with those incurred in the iron, namely, hysteresis and eddy currents, raise the temperature of the armature, but while this temperature may perhaps be kept within limits by especially good ventilation, as has been explained, the efficiency of the machine will be lowered to an undesirable degree. In very small machines, the circular mils per ampere may be as small as 300, while in larger machines it may be as much as 800 or 1,000. Since there must be a certain amount of copper in the conductors per ampere, it is evident that the greater the number of amperes per inch of circumference of armature, the more room will be required in the slots. Now, the slots cannot be made indefinitely deep; first, because the inductance of the coils is increased, and, second, because the deepening of slots with parallel sides narrows down the width of the teeth at their roots and chokes the flux at this point. On this latter account, small diameters require shallow slots, and fewer ampere-conductors per inch can be accommodated than with larger diameters of armature. The ampere-conductors per inch usually vary from 300 to 700. On fan-motor sizes, it may be less than 100. For the machine to be designed later, 550 ampere-conductors will be assumed.

11. It will be noticed that where the current density in the copper is high, that is to say, where the circular mils per ampere are low, there will be greater heating per pound of copper than where the current density is low. Now, in designs where there are many amperes per inch of circumference, there must be considerable copper per inch, and in order that the heating at the surface shall not be excessive, the current density in the copper must be lower than where the amperes per inch are less. That is to say, the copper per inch should increase more rapidly than the ampere-conductors in order to keep the heat liberated per square inch of armature surface at the same value.

12. Speed in Revolutions per Minute.—The speed of electric generators that are direct-connected to engines or other prime movers must be designed to agree with that of

the driving agent, but dynamo speeds are not otherwise closely restricted. Where the machines are belt-driven, the speed of the belts should be from 4,000 to 5,000 feet per minute for machines with pulleys over 15 inches in diameter, and it has been found desirable to limit the peripheral speed of armatures to about the same values, although some classes of dynamos have peripheral speeds of 6,000 feet per minute, or even higher.

13. Many very satisfactory moderate-speed machines run from 2,500 to 4,000 feet per minute, and 4,500 feet per minute is not an unusual value. Engine-type direct-connected machines, of course, have much lower peripheral velocities, especially if intended to be direct-connected to Corliss or other slow-speed type of engine. We will assume that the machine is to be belt-driven and the revolutions per minute are not restricted, so it will be best to restrict the peripheral speed to 4,000 feet per minute. If D is the diameter of the armature in inches, and the peripheral velocity is 4,000 feet per minute, then the speed in revolutions per minute will be $S = \frac{4{,}000 \times 12}{\pi \times D}$, because 4,000 $\times$ 12 gives the number of inches traveled by the circumference per minute, and $\pi \times D$ is the circumference in inches. This value is to be put in the fundamental formula **1**, in place of S.

14. It will thus be seen that the quantities to be assumed in the fundamental formula for the output may have widely differing values, depending on the size and type of machine. To lay down a set of rules for determining each quantity might be possible, but the information from which these rules would be derived is the private property of the various electric manufacturing companies and could not be obtained, therefore, for such a purpose. It is the skill of the electrical engineer in properly proportioning the quantities to each other that insures the success of a particular design, and a very wide experience is necessary before his judgment becomes reliable.

15. General Dimensions of Armature.—Referring again to the fundamental formula,

$$\text{watts} = \frac{\% \, \pi^2 \, D^2 \, L \, \mathbf{B}_g \, K \, S}{10^8 \times 60}$$

For each of these quantities except D, values as follows have been taken:

$$\text{watts} = \frac{\text{output}}{U_e} = \frac{100{,}000}{.96} = 104{,}166, \text{ or, say, } 104{,}200$$

$$\% = .75$$

$$L = h \, D = \frac{D}{4}$$

$$\mathbf{B}_g = 55{,}000$$

$$K = 550$$

$$S = \frac{4{,}000 \times 12}{\pi D}$$

Substituting these values gives

$$104{,}200 = .75 \times \pi^2 \times D^2 \times \frac{D}{4} \times 55{,}000 \times 550$$

$$\times \frac{4{,}000 \times 12}{\pi D} \times \frac{1}{10^8 \times 60}$$

whence,

$$D^2 = \frac{104{,}200 \times 4 \times 10^8 \times 60}{.75 \times 3.1416 \times 55{,}000 \times 550 \times 4{,}000 \times 12} = 731$$

$$D = \sqrt{731} = 27.04'', \text{ or, say, } 27''$$

$$L = \frac{D}{4} = \frac{27}{4}'' = 6\tfrac{3}{4}''$$

$$S = \frac{4{,}000 \times 12}{\pi D} = \frac{4{,}000 \times 12}{3.1416 \times 27} = 566 \text{ r. p. m.} = \text{say } 575$$

16. Armature Conductors.—It is usually more difficult to wind generators for 500 volts than for 250 or 125 volts, especially the smaller sizes, and it is therefore best to try the 500-volt windings first. The total current output of the generator at 500 volts is $\frac{100{,}000}{500} = 200$ amperes. If the few amperes flowing through the shunt coils be neglected, as may be done, the total armature current may be taken as

200 amperes. Now, taking a single series-winding for trial, there will be but two paths, and 100 amperes will be the current per path or per conductor. With 550 ampere-conductors per inch and 100 amperes per conductor, the total number of face conductors will be

$$\frac{550 \times \pi D}{100} = \frac{550 \times 3.1416 \times 27}{100} = 466$$

because the number of inches in the periphery is πD, and $550 \times \pi D$ will give the total volume of current in all the conductors. This divided by the current per conductor evidently gives the number of conductors.

17. Minimum Number of Commutator Segments. The average volts per commutator segment should not be more than about 15, or there will be danger of the machine *flashing over* from positive to negative brushes. The least number of segments between adjacent brush points should then be $\frac{500}{15} = 33.333$, and since there are six poles, the total number of segments should not be less than $6 \times 33.333 = 200$. With 466 face conductors arranged into a winding with one turn per coil, or two face conductors, there would be 233 coils and segments, which number is greater than 200, and is therefore safe.

For 250 volts, the average volts per segment should not be greater than 10, and for 125 volts not greater than 7. There is not much liability of these lower voltages flashing over, but other requirements fix the above limits. For 125-volt machines, for example, with a modern commutator arranged for carbon brushes, if the volts per segment were made 10, there would be but 12 segments from brush point to brush point, and each of these would then be very thick and would not make a good running commutator. These values are all taken from practice and are known to be satisfactory. Of course, they must all be exceeded in very small machines, for the segments should not be much less than $\frac{3}{16}$ inch thick in any case, because the percentage of mica in the commutator then becomes so great that it is liable to

wear unevenly and prove unsatisfactory. The product of the inductance of the coils and the current in each conductor must be kept low in order to commutate the currents successfully, and in machines of very large current outputs, this may necessitate the use of very many more segments than the limiting values just given would indicate. At best, the foregoing method of approximating the number of segments is but a rough guide, and a complete investigation of a particular winding for inductance and sparking is too complicated to be given here.

18. Number of Slots and Coils.—For a single series-winding, the number of commutator segments and the number of coils must fit the formula

$$C = \frac{p}{2} y \pm 1$$

where C is the number of segments, and y is any whole number. In this case,

$$C = \tfrac{6}{2} \times 78 - 1 = 233$$

therefore 233 coils will wind all right. However, 233 is a prime number, and it would therefore be necessary to have 233 slots to accommodate the winding. The expense of punching the disks and of winding the coils increases with the number of slots, and it would be better to wind 2, 4, or 5 coils in each slot. Three or 6 coils per slot being divisible by $\frac{p}{2}$, or 3, makes the total number of coils divisible by $\frac{p}{2}$, and will not wind properly into a single series-winding. Four coils per slot will answer very well. The student will understand the arrangement of the 4 coils by referring ahead to Fig. 18. The 4 coils are taped together to form a single element that occupies the top and bottom halves of two slots separated by the distance between centers of poles. The number of coils of one turn each is therefore four times the number of slots. The nearest number to 233

divisible by 4 is 232, and the number of slots required is 58. We have, then,

$$C = \frac{p}{2} y \pm 1 = \frac{6}{2} \times 77 + 1 = 232$$

This number will therefore wind. If too few slots are used, the machine will be liable to hum when running. The coils should each span about one-sixth of a circumference, or 10 slots, since 10 is the nearest whole number to $\frac{58}{6}$.

19. Armature Conductor.—The size of the conductor required to carry 100 amperes may be determined by allowing about 600 circular mils per ampere. A copper strip $\frac{5}{8}$ inch wide and .075 inch thick with rounded edges, as shown in Fig. 1, has an area of 58,125 circular mils, or 581 circular mils per ampere of current. This area consists of a rectangle .075 in. × .550 in. and two semicircles .075 inch in diameter.

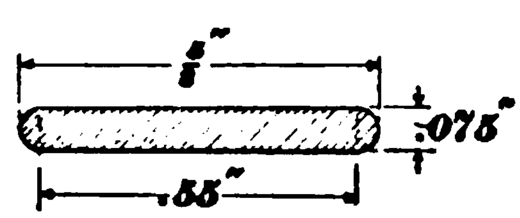


FIG. 1

The rectangle has an area of 75 × 550 = 41,250 square mils, or $\frac{41,250}{.7854}$ = 52,500 circular mils, approximately. The two semicircles combined form a circle .075 inch in diameter; therefore, their area is 75 × 75 = 5,625 circular mils. The total area of the conductor, then, is 52,500 + 5,625 = 58,125 circular mils.

20. Insulation of Armature Conductors.—To insulate the conductors from each other, alternate conductors should be wrapped with cotton tape, half lapped, and the four conductors that are to go into one slot should then be taped together. The tape, which is usually about .009 inch thick by $\frac{3}{4}$ inch wide, is double thick on a side on account of the lapping, or .018 inch on a side, so that each wrapping adds .036 inch to the thickness. The width of the four coils complete will be about as follows: There are two wrappings of tape on the conductors and one over all, or three wrappings of

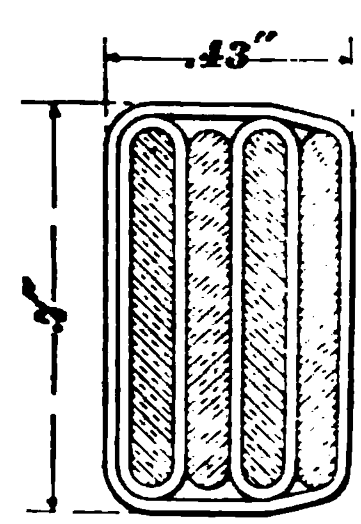


FIG. 2

.036 inch make a total for insulation of .108 inch; the thickness of the four copper bars is .075 inch × 4 = .3 inch, making a total of .408 inch. Allowing .020 inch clearance, or extra room, makes the total .428 inch, which may be taken as .43 inch. In the depth there are but two wrappings over the conductors, so the total thickness of insulation is .072 inch; the copper itself is .625 inch deep, making a total of .697 inch, or .7 inch. See Fig. 2.

21. Slot Insulation.—The slots should be insulated by a cell made up of a sandwich, as it is called, of two layers of presspaper each .015 inch thick, with a thickness of oiled muslin 010 inch thick between. Oiled muslin is a good quality of muslin dipped in linseed oil and dried. Its thickness varies from .007 inch to .015 inch, depending on the quality of the muslin. The thickness of the cell would be about .040 inch, which should withstand 2,000 volts or more without breaking down or being punctured. The cell is first put into place for winding; then the bottom coil is inserted, and over it a strip of the same sandwich is placed to separate the upper and lower coils in the same slot. After the upper coil is in place, the cell is lapped over it at the top and a wooden or fiber wedge driven into the nicks at the top of the slots to retain the windings against the centrifugal force while running. This construction avoids the use of binding wires over the armature core; these bands are somewhat liable to be broken, especially where small air gaps are used.

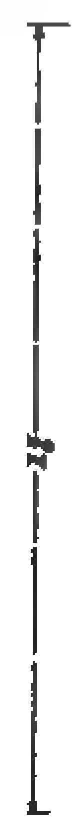


FIG. 2

22. Dimensions of Slot.—The width of the slots is the sum of two thicknesses of the cell, one on each side, and of the coil, or 2 × .040 + .43 = .51 inch, a little over ½ inch. For the total depth,

there must be added to the depth of two coils, four thicknesses of the cell and the thickness of the hard-wood retaining wedge or $(2 \times .7) + (4 \times .040) + \frac{3}{16} = 1.7475$ inches, or 1.75 inches. Fig. 3 shows the shape of the slot and the arrangement of the conductors.

23. Calculation of Total Flux.—From the equation $E = \frac{p \Phi S}{60 \times 10^8} \times \frac{Z}{m}$, the total flux from or to one pole is $\Phi = \frac{E \times 10^8 \times 60 \times m}{Z p S}$, in which E is the total E. M. F. developed in the armature. In the present design, assume, say, 15 volts as the loss in volts due to the resistance of the armature winding, commutator, brushes, series-field, and all connections; then, since the voltage at the terminals is to be 500, the value of E in the above equation is 515 volts. It has been decided that m, the number of paths through the armature winding, is 2; Z, the total number of face conductors, is 464; p, the number of poles, is 6; and S, the revolutions per minute, is 575. Hence, $\Phi = \frac{515 \times 10^8 \times 60 \times 2}{464 \times 6 \times 575}$ $= 3,860,000$ magnetic lines of force.

24. Density in Teeth.—There are 58 teeth in all for six poles, so the number per pole is $\frac{58}{6}$; but, since the poles cover only 75 per cent. of the armature, the average number of teeth opposite a pole is $\frac{58}{6} \times .75 = 7\frac{1}{4}$. So the flux of 3,860,000 lines passes through an average of $7\frac{1}{4}$ teeth. The density at the tooth roots is an important point and should be determined. The diameter of the armature is 27 inches and the slots are $1\frac{3}{4}$ inches deep, so the diameter at the roots is $23\frac{1}{2}$ inches. The distance from center to center of slots at the roots is $\frac{23.5 \times 3.1416}{58} = 1.273$ inches. The slots are .51 inch wide, so the width of a tooth at the roots is $1.273 - .51 = .763$ inch. See Fig. 4.

The armature core is to be $6\frac{3}{4}$ inches long, parallel to the shaft, and in the middle of this there should be a ventilating duct say $\frac{1}{2}$ inch wide, leaving $6\frac{1}{4}$ inches as the length of the

punchings. Now, in order to prevent eddy currents from disk to disk, they should be insulated from each other, and

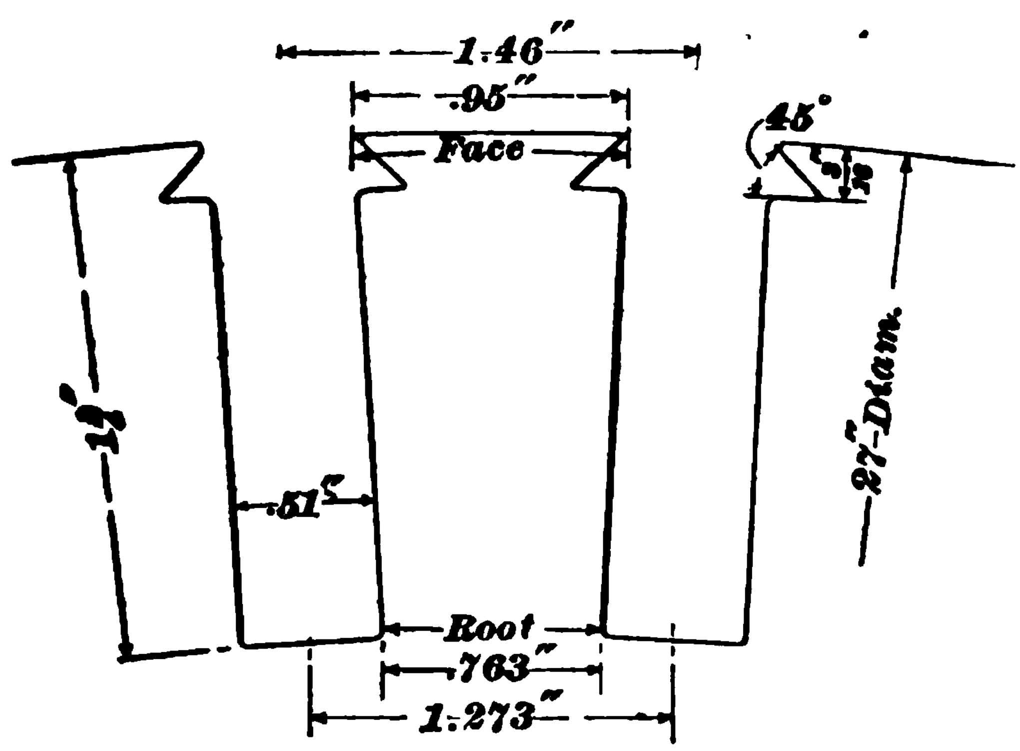


FIG. 4

a very good way of doing this is to coat them with japan or put punchings of thin paper between them. The iron punchings are usually about .015 inch thick, so that even the thinnest insulation occupies a considerable percentage of the room. As about 85 per cent. of the punchings may be taken as iron, the net length of iron in the armature core is $.85 \times 6\frac{1}{4} = 5.31$ inches.

The area of iron at the roots of each tooth, then, is $5.31 \times .763 = 4.05$ square inches. The area of $7\frac{1}{4}$ teeth is then 29.4 square inches. Through this area the total flux of 3,860,000 lines pass, so the density at the tooth roots is $\frac{3,860,000}{29.4} = 131,300$ lines per square inch. This density is about right; it should be under 140,000 lines and preferably over 120,000 lines. A high density at this point is of importance in preventing, or tending to prevent, the effects of armature reaction.

When the magnetic density in the teeth is higher than 100,000 lines per square inch, quite an appreciable part of the magnetic flux will pass up through the slots and other non-iron paths between the teeth, and in the above computations it is assumed that all of the magnetic flux passes

through the iron. To correct the tooth-root densities by allowing for the flux that passes up through the slots is ordinarily a needless calculation, for the error involved by computing in the foregoing manner is not of sufficient amount to be counted.

25. Inside Diameter of Core.—The magnetic flux from each pole divides in the armature core below the teeth, half

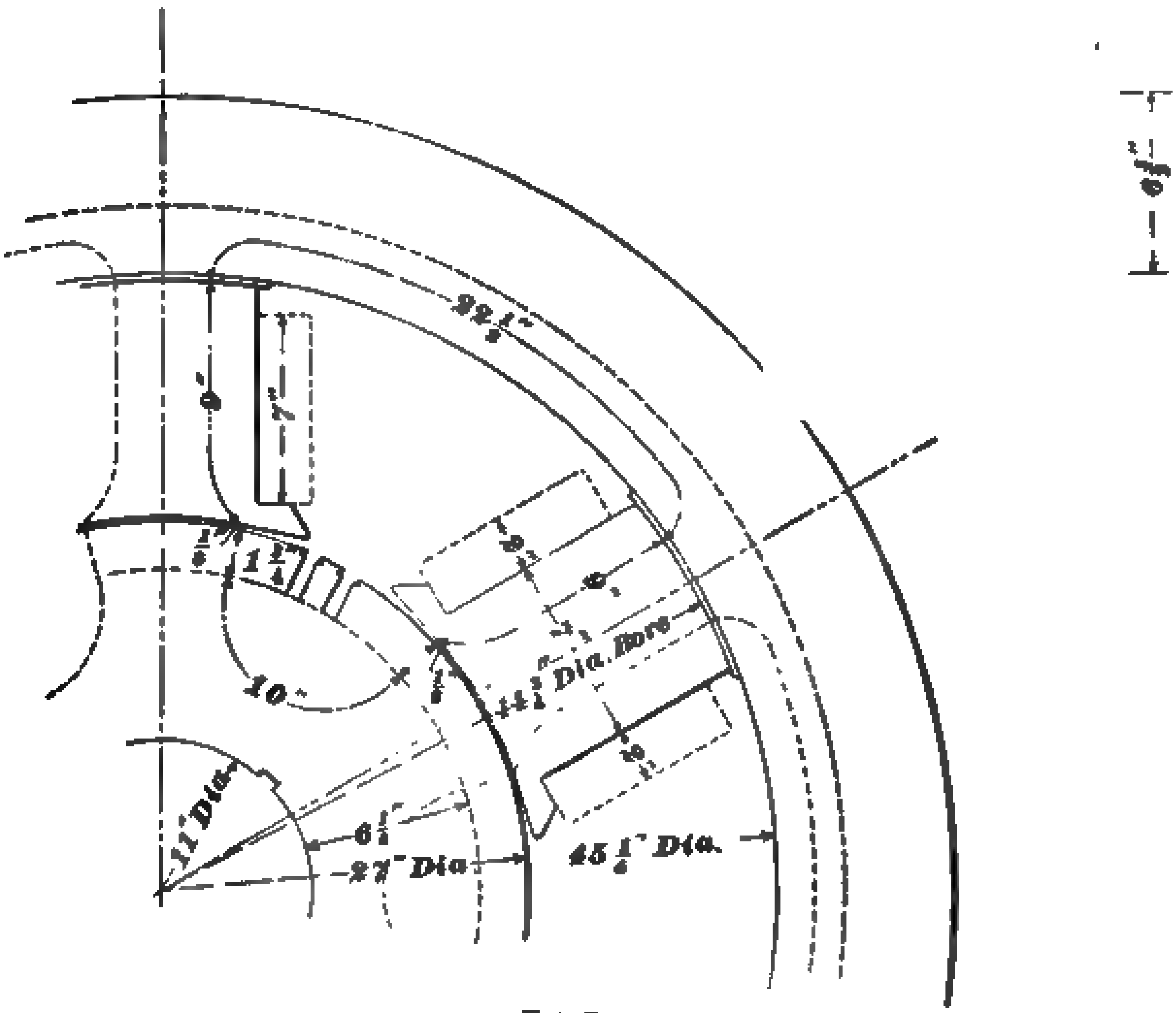


FIG. 5

going to each side (see Fig. 5), and, therefore, the flux through the armature core below the teeth is $\frac{3,860,000}{2}$ = 1,930,000 lines. The magnetic density in the armature core is usually from 50,000 to 100,000 lines per square inch If the lower value is used, the amount of iron required will of course be greater, but the losses due to hysteresis will be much less, while the reverse is true for the higher densities Say a density of about 60,000 lines is assumed for the present design; then, the area of the core below the teeth should be

$\frac{1930000}{60000} = 32.2$ square inches, approximately. Now, the net length of iron in the core has been found to be 5.31 inches, so the radial depth of the iron in the core below the slots should be $\frac{32.2}{5.31} = 6.06$ inches. We will make this depth, say, $6\frac{1}{4}$ inches, in order to have even dimensions. The area of cross-section of the iron in the path in the armature core will then be $6.25 \times 5.31 = 33.2$ square inches. The radius of the bottom of the slots is $11\frac{3}{4}$ inches, and deducting $6\frac{1}{4}$ inches from this leaves $5\frac{1}{2}$ inches for the radius of the central hole in the punchings, or 11 inches for the diameter. These dimensions are indicated in Fig. 5, which also shows some of the field dimensions calculated later on.

HEATING CALCULATIONS

26. Hysteresis Loss.—As has been explained, there are two limits to the output of a dynamo, the temperature rise, or heating limit, and the sparking limit. To determine whether a design approaches these limits is somewhat difficult, especially in regard to sparking. To calculate the probable rise in temperature, it is necessary to compute the losses per square inch of surface in the armature, as has already been explained. These losses consist of hysteresis and eddy-current losses in the iron of the armature core, and of I^2R losses in the conductors. In a six-pole dynamo there will be 3 cycles per revolution, or at 575 revolutions per minute, $\frac{575}{60} \times 3 = 28.75$ cycles per second. The density at the tooth roots at full load is 131,300 lines per square inch, and the width of a tooth at this point is .763 inch. At the tops of the teeth the width is .95 inch, so, since the same flux goes through the top as through the roots, the density at the tops is $131{,}300 \times \frac{.763}{.95} = 105{,}500$ lines per square inch, nearly. The average density in the teeth, then, is the average between 131,300 and 105,500, or 118,400 lines per square inch. The density in the core beneath the teeth is about 60,000.

The width of a tooth at the top is .95 inch, and at the bottom is .763 inch; so the average width is .856 inch. The depth of a tooth is 1.75 inches, and the net length of iron is 5.31 inches; so the volume of 58 teeth is $58 \times .856 \times 5.31 \times 1.75 = 461$ cubic inches. The volume of core below the teeth is $\frac{\pi}{4} \times (23.5^2 - 11^2) \times 5.31$ inches $= 1{,}798$, or, say, 1,800 cubic inches. From the table of hysteresis losses, it is found that for a density of 115,000, the loss per cubic inch per cycle per second is .0362 watt, while for 120,000 it is .0387 watt; hence, for 118,400 it would be about .0379 watt per cubic inch per cycle per second. The hysteresis loss in the teeth is, then, $461 \times .0379 \times 28.75 = 502$ watts. From the table, the loss for 60,000 lines density is .0128 watt, so the hysteresis loss in the core proper is $.0128 \times 1{,}800 \times 28.75 = 663$ watts, approximately. The total loss due to hysteresis, then, is 1,165 watts.

27. Eddy-Current Loss.—It is impractical to compute the eddy-current losses, as has been explained, but they may be estimated approximately as proportional to the hysteresis loss. Suppose it is assumed that with the care the laminations are insulated in the present design, the loss is three-fourths as large as the hysteresis loss, or $\frac{3}{4} \times 1{,}165 = 875$ watts, approximately. When the machine is built, this should be checked up with the tests and the assumed factor corrected in future similar designs. The total iron losses then become 2,040 watts, or a little more than 2 per cent. of the output.

28. I^2R Loss in Slots.—The heat developed by the I^2R losses in that part of the armature winding that is in the slots may be calculated as follows: The resistance of a single face conductor when warm is $R = \frac{\text{length in inches}}{\text{circular mils}} = \frac{6.75}{58{,}125}$. In each conductor is 100 amperes, and there are 464 face conductors in all, so the total loss is $464 \times 100^2 \times \frac{6.75}{58{,}125} = 539$ watts. It must not be thought that this is all of the

armature $I^2 R$ loss; it is only that part which is developed within the slots, and the part developed within the end connections has yet to be considered. The total watts developed in the core and slots is $2,040 + 539 = 2,579$. Now, this heat has to be radiated from the surface of the armature core and of the ventilating flues, etc. The outside cylindrical surface of the core is $\pi D L = 3.1416 \times 27 \times 6.75 = 573$ square inches. Each square inch of this surface must then radiate $\frac{2579}{573} = 4.5$ watts.

From Table IV, Part 2, it is seen that, for a peripheral speed of 4,000 feet per minute, which is the speed of this armature, 4.5 watts per square inch of core surface can be radiated, and in the design there is just 4.5 watts developed per square inch. The ventilation must therefore be made good; for, otherwise, the dynamo will run too hot, as there is no margin.

WINDING FOR 250 VOLTS

29. Thus far the 500-volt armature winding alone has been considered. For 250 volts, the number of face conductors in series on a path between brushes should be halved. Half of 232, or 116 segments, would be too few for a 250-volt commutator, because the average volts per bar would be too high, and it will therefore be necessary to use a double series-winding. This winding requires that the number of coils $C = \frac{p}{2} \times y \pm 2$, or $232 = \frac{6}{2} \times 78 - 2$. The pitch of the winding, then, is 78; whereas before for the single-series winding it was 77. As has been already explained, the change from a single to a double series-winding changes the number of paths from two to four, and since the total number of conductors on all paths remains the same, the number on each must be halved, as is the voltage also. The number of paths being doubled, the current-carrying capacity of the winding is also doubled, and since the voltage is halved, the output is not changed.

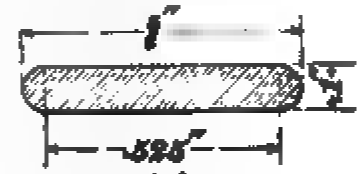
WINDING FOR 125 VOLTS

30. Style of Winding.—For 125 volts, a quadruple winding would give the correct voltage, but it could hardly be kept from sparking. In fact, the double series-winding used for 250 volts is objectionable for high speeds and also for high voltages, so the quadruple winding is out of the question. A single series-winding for this voltage would have one-fourth as many segments as for 500 volts, or 58, which would give an average voltage of 12.9 per segment, and it has been stated that this last should not exceed 7 volts. Therefore, this winding should have at least $\frac{125}{7} \times 6 = 107$ segments. A double series-winding with $2 \times 58 = 116$ segments would do, but a single parallel winding with $3 \times 58 = 174$ segments would be far superior as regards freedom from sparking. A parallel winding has as many paths as poles, or in this case six, while a single series-winding has but two, so a single parallel winding, therefore, will require three times as many segments as a single series-winding for the same voltage.

31. Cross-Connecting Rings.—As has been explained, a parallel winding is liable to peculiar commutator phenomenon called bucking, and to prevent this, the winding should be cross-connected in the manner previously described. In the present design, four cross-connecting rings are about as few as could be relied on to prevent bucking. These rings should be connected to points that always remain at the same potential, or to points two poles apart. Therefore, the rings should be connected as follows: Ring No. 1 to segments 1, 59, and 117; ring No. 2 to segments 16, 74, and 132; ring No. 3 to segments 30, 88, and 146; ring No. 4 to segments 45, 103, and 161.

32. Size and Arrangement of Conductor.—Using the same number and size of slots as before, there would be three coils per slot; 100 kilowatts at 125 volts is equivalent to 800 amperes, so each of the six paths should carry

133 amperes. A conductor .1 in. $\times \frac{5}{8}$ in. [see (*a*), Fig. 6] has an area as follows: $100^2 + 525 \times 100 \times \frac{4}{\pi} = 76{,}845$ circular mils, or 577 circular mils per ampere. To insulate the conductors, the outside bars are taped, leaving the middle one bare; then the three are taped together, as shown at (*b*), Fig. 6. The width of the three conductors is .3 inch, and three wrappings of tape at .036 inch makes .108 inch, which leaves .022 inch clearance to bring the coil up to .43 inch wide, the width of the former coils. See Fig. 2.



(*a*)

(*b*)

FIG. 6

DESIGN OF COMMUTATOR

33. Diameter and Peripheral Speed.—The commutator on modern machines has ordinarily a diameter between .6 and .8 of the diameter of the armature. In this design the commutator will be made, say, 19 inches in diameter, or about .7 of the armature diameter. The peripheral speed of the commutator is best kept below 2,500 feet per minute, although many run as high as 3,500 or 4,000 feet per minute; but if a commutator gets out of true when running at a high peripheral speed, it will rapidly grow worse. The peripheral speed of a 19-inch diameter surface running at 575 revolutions per minute is 2,860 feet per minute.

34. Thickness of Brushes.—With poles covering 75 per cent. or more of the armature surface, the neutral region on the commutator surface is usually so narrow that wide brushes short-circuit active coils and thus cause the commutator and armature to heat unnecessarily. Since a given distance around on the commutator means a greater difference of the potential on a high-voltage than on a low-voltage machine, it follows that the brushes should be thinner for 500 volts than for 125 or 250 volts. Just what thickness of brush can be

used in any given case is usually determined by trial after the machine is built; but for purposes of calculation, it may be assumed, from the known results in similar designs, that for the 500-volt windings $\frac{7}{16}$-inch brushes may be used; $\frac{5}{8}$-inch for 250 volts, and $\frac{3}{4}$-inch or $\frac{7}{8}$-inch for 125 volts. There is no reliable rule giving the number of segments the brushes should span, and such rules are not even approximate, as can be seen by applying them to the present design.

35. Brush-Contact Area.—For 500 volts, the current developed is $\frac{\text{watts}}{\text{volts}} = \frac{100{,}000}{500} = 200$ amperes. This current goes from the negative brushes into the commutator, and from the commutator to the positive brushes, so that the 200 amperes is carried by three negative brush points, and at each brush point 67 amperes must pass either in or out of the commutator. Now, the current density at the contact surface for carbon brushes should not be more than 40 amperes per square inch, 30 to 35 amperes being good values. For copper brushes, the density may be as high as 100 amperes per square inch, and it is frequently higher than this. Copper brushes are little used on modern direct-current machines. At 30 amperes, each brush point would require about 2.2 square inches area of contact surface. Making the brushes say $\frac{7}{16}$ inch thick by $1\frac{3}{4}$ inches wide, each would have an area of .765 square inch, or three of them on each brush stud would have a combined area of 2.3 square inches, which is about the required amount.

For 250 volts the current output is 400 amperes, so 4.4 square inches contact area are required per brush point. Using $\frac{5}{8}'' \times 1\frac{3}{4}''$ brushes, each would have an area of 1.09 square inches, so that four of them would be required at each brush point.

For 125 volts, in the same way, 8.8 square inches per brush point are required, which is obtained by using $\frac{7}{8}'' \times 1\frac{3}{4}''$ brushes, six at each brush point.

This completes the electrical design of the armature and the commutators. The mechanical design and construction of these will be taken up later.

THE MAGNETIC CIRCUIT

36. Pole Pieces.—The pole pieces will be built up of punchings about $\frac{1}{32}$ inch thick, riveted together between cast-steel, malleable-iron, or wrought-iron end plates $\frac{3}{8}$ inch thick. As there are six poles covering 75 per cent. of the armature, each must include an angle of $.75 \times \frac{360°}{6} = 45°$.

37. Flux in Pole Pieces.—The flux to or from each pole has been found to be 3,860,000 lines. Now, with similar designs it has been found that the coefficient of magnetic leakage varies from 1.1 in very large machines with short air gaps to 1.2 in very small machines with comparatively long air gaps. Assuming 1.14 for the leakage factor in the present design, the total magnetic flux in the pole pieces becomes $1.14 \times 3,860,000$, or 4,400,000, approximately.

38. Magnet Cores.—The density in the magnet cores should be from 85,000 to 95,000 lines per square inch. It is possible to use as high as 100,000, or even more, but this requires that only iron of the best magnetic qualities be used, otherwise the ampere-turns required to force the flux through the iron will be excessive. Both iron and steel, as at present manufactured, are quite irregular in magnetic qualities, and a low density usually will save the expense of having to reject parts made up of iron of which the poor quality was not suspected until finished.

At 95,000 lines per square inch, the area of the magnet cores for 4,400,000 lines should be 46.32 square inches. These cores will be about 95 per cent. iron. The percentage of iron is greater than on the armature, because the punchings are thicker and no insulation is required between them. The gross area of the cores, then, should be $\frac{46.32}{.95} = 48.76$, or, say, 7 inches square, or 49 square inches. The pole pieces then are $\frac{1}{4}$ inch longer than the armature core, which was $6\frac{3}{4}$ inches. The steel end plates on the poles would have eddy currents induced in them if they extended to the pole face, so it is

customary to cut them short ¼ inch or more. In this case, then, the pole face will be only 6½ inches long, while the armature is 6¾ inches.

The pole-piece punchings are 7 inches wide at the magnet cores, while over the pole tips, or horns, as they are called, the punchings are about 10⅝ inches wide (see Fig. 7). The punchings are made with shoulders at *a* to support the field coils. The dimension *b* should be such that the magnetic

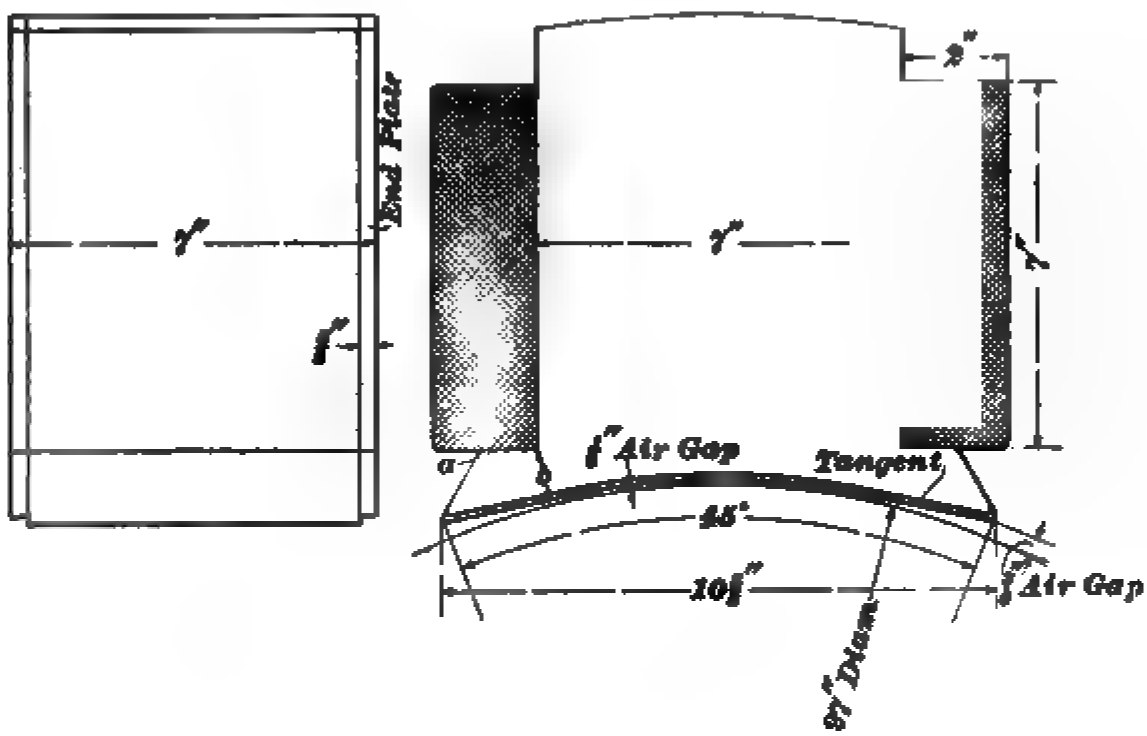


FIG. 7.

density at the contracted point will be about 130,000 lines per square inch. The tips, or horns, project about 1¾ inches on each side from the body of the pole piece, and the length of the arc of the pole face is about 10⅝ inches. Now, from this pole face, 3,860,000 lines pass to or from the armature; therefore, about $\frac{1\frac{3}{4}}{10\frac{5}{8}} \times 3{,}860{,}000 = 636{,}000$ lines pass from the tips. Since there is considerable leakage from pole tip to pole tip, say the flux through *b* is taken as $1.14 \times 636{,}000 = 725{,}000$ lines. At a density of 130,000, the area of *b* should be 5.58 square inches. The net length of iron in the poles is $.95 \times 7 = 6.65$ inches; so the dimension *b* in Fig. 7 should be $\frac{5.58}{6.65} = .839$ inch, or say, ⅞ inch. In order to

estimate the ampere-turns required for the magnetic circuit, it is necessary to assume some dimension for the radial length of the magnet cores. The magnet cores are usually from 1 to 1.5 times as long as they are wide, so as a basis for further calculations we shall take the dimensions shown in Fig. 5, making the inside diameter of the yoke 45¼ inches and the bore of the surfaces where the poles fit on, 44¾ inches. These dimensions can, if found necessary, be modified later after the space for the field coils has been accurately determined.

39. Air Gap.—In order to get a good magnetic fringe for commutation, and also in order to prevent humming, the air gap at the pole tips is usually made considerably greater than in the middle of the pole. In the case where solid poles are used, the same effect is accomplished by nosing the pole tips, as it is called, i. e., making them pointed, so that a tooth enters under the poles gradually. The nosing is usually not greater than is necessary to allow one tooth to pass completely under the pole while the next one is just under the tip of the nose. In the present problem, the air gap is assumed to be ⅛ inch, except at the tips, where it is ⅜ inch. The bore of the poles, then, is 27¼ inches, and it is further assumed that the air gap increases by a tangent line from the ⅛-inch gap to the ⅜-inch gap. See Fig. 7.

40. Yoke.—Assuming that the yoke is made of cast steel, it will be quite safe to work it at a density of about 75,000 lines per square inch. If it is certain that the quality of the steel will always be good, a density of 90,000 or even higher would be better, since less material would be required, but the magnetic quality of steel castings varies considerably, and since it cannot be readily determined whether a particular casting is good or bad until it is machined, a considerable loss is incurred if castings must occasionally be rejected; for this reason the lower density is preferable. The length of the magnetic path in the yoke is considerable, and if the iron requires many ampere-turns per inch to set up the flux, a considerable part of the available ampere-turns

of the field coil will be required at this point; the remainder may not be sufficient to set up the flux in the rest of the magnetic circuit, so the total flux will be too small. The voltage, therefore, will be too low, and unless the speed is increased, the windings or the castings will have to be changed.

The flux from each pole divides at the yoke, half going right and half going left, so that the yoke section must carry half the flux in the poles, or about 2,200,000 lines. At 75,000 lines per square inch, the area required for the section of the yoke is thus 29.3, or, say, 30 square inches. In order that the yoke shall be strong and stiff and at the same time have a heavy appearance, which is considered desirable in modern machinery, it will be made channel-shaped in cross-section, as shown in Fig. 5.

41. A preliminary sketch of the field should now be made, as shown in Fig. 5, and the general dimensions of the machine may be thus determined. The mean path of the flux is shown by the dotted lines. These are lines that divide the middle of the section of the magnetic path. From the sketch, the length of the mean paths in the various parts can be measured off by means of dividers.

42. It was assumed that the average air-gap density should be 55,000 lines per square inch, and while this average air-gap density is about correct, still it is of no use in

FIG. 8

determining the number of ampere-turns required to set up the flux across the air gap. In order to obtain actual air-gap

densities, the paths or courses of the lines across the gap must be known, and since this is somewhat complicated, approximations are made for the purpose of simplifying the calculations. In Fig. 8, where the ratio $\frac{B}{A}$ has a value less than from 2 to 3, the lines of force spread out from the teeth and fill the upper end of the slots, forming a fairly uniform field in the air gap proper, and the actual density is very little increased on account of the slots removing a part of the armature surface. That this is practically correct is shown by the fact that pole-face eddy currents are negligible in such cases, as has already been stated. If the ratio $\frac{B}{A}$ is greater than 3, the lines of force spread out after the manner

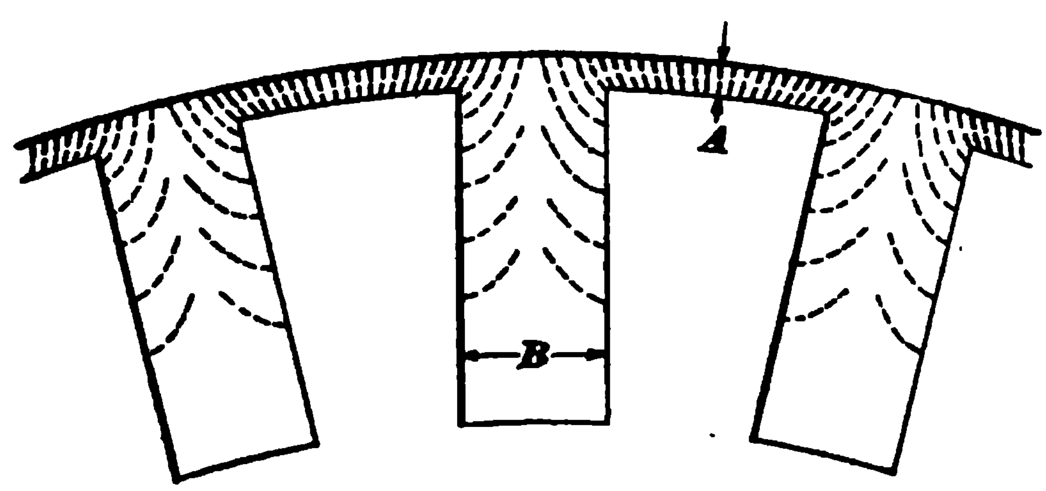


FIG. 9

of Fig. 9, but the density opposite the teeth is much greater than opposite the slot openings.

43. For purposes of calculation, it has sometimes been assumed that the lines of force spread as in Fig. 10. In this

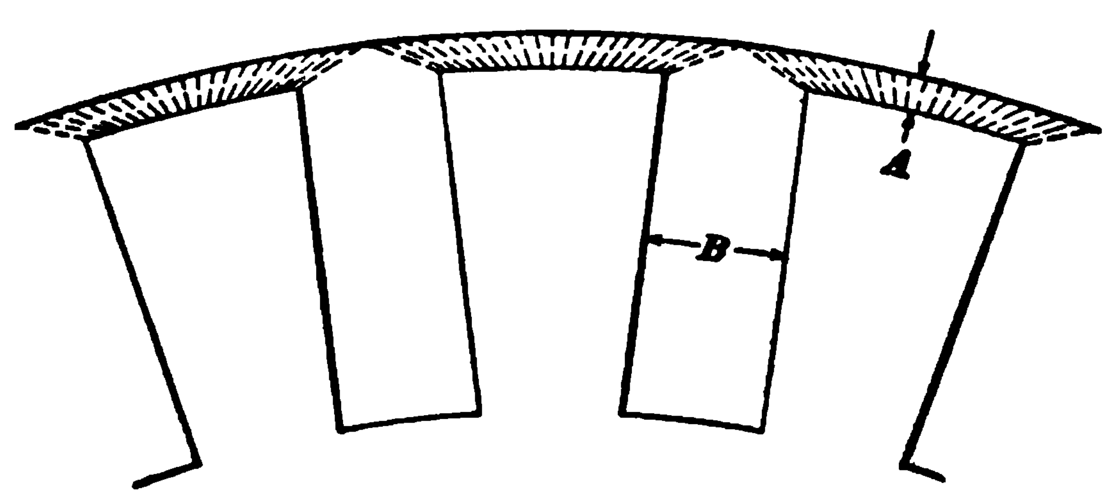


FIG. 10

case the approximate density may be taken as the quotient obtained by dividing the flux per pole by the average of the

area of the pole face and of the tops of the teeth. This rule is simple and gives fair results when $\frac{B}{A}$ is about 4. For smaller values of $\frac{B}{A}$ it will give too high densities, and the ampere-turns for the air gap will be overestimated. A better rule is to take as the area of the air gap the sum of the areas of the teeth, assuming the width of each tooth to be increased by a strip A inches wide on both sides. Ordinarily, no attention need be paid to the area of the teeth removed by ventilating ducts, or to differences in length between armature and field, as these will not greatly modify the values.

44. In the design at hand, the teeth are .95 inch wide at the top (see Fig. 4), and the air gap is $\frac{1}{8}$ inch, so the assumed equivalent width of a tooth is $.95 + (2 \times \frac{1}{8}) = 1.2$ inches, and the length parallel to the shaft is $6\frac{3}{4}$ inches, or the area of the air gap per tooth is $1.2 \times 6\frac{3}{4} = 8.1$ square inches. Now, there are $7\frac{1}{4}$ teeth opposite a pole, so the area to be taken for the air gap at each pole is $8.1 \times 7\frac{1}{4} = 58.7$ square inches. The above rule is to be used unless the ratio $\frac{B}{A}$ is less than, say, 2 or $2\frac{1}{2}$, in which case the whole area of the armature beneath the pole is to be taken.

The magnetic circuit as computed is made up as shown in Table II.

TABLE II

Part	Material	Area of Path Square Inches	Length of Path Inches
Armature core..	Annealed punchings	33.2	10
Teeth at roots..	Annealed punchings	29.4 } Average	$2 \times 1\frac{3}{4} = 3\frac{1}{2}$
Teeth at tops....	Annealed punchings	36.6 } 33	
Air gaps........	Air	58.7	$2 \times \frac{1}{8} = \frac{1}{4}$
Pole pieces......	Annealed punchings	46.5	$2 \times 9 = 18$
Yoke............	Steel casting	30	$22\frac{1}{2}$

COMPUTATION OF FIELD WINDINGS

45. Magnetization Curve. — To compute the field windings a magnetization curve, also called a saturation curve, is required. This is a curve showing the relation between the total flux per pole and the ampere-turns required to set up this flux. If the speed is fixed, the volts developed depend on the flux, and sometimes the curve is plotted between the volts developed and the ampere-turns. This last curve may be readily obtained experimentally from a completed dynamo, but it is more convenient for purposes of calculation to reduce the volts to flux per pole, for the armature may be run at other speeds than that of the test, and also other windings may be provided for other voltages, so that the volts would not be the same in all cases even though the flux per pole be kept at a certain desirable value. In other words, a change in the speed or armature winding would change a curve plotted between the volts and ampere-turns, but would not change a true saturation curve of a certain dynamo. These curves are very similar in shape to the magnetization curves already given for the various magnetic materials, only the latter are for a single material while the former are for a complete dynamo.

To compute the magnetization curve for the foregoing dynamo, assume several values for the flux per pole and compute the ampere-turns required for each; plot the points on cross-section paper, and through them draw a smooth curve. The values assumed for the flux should be near that at which the machine is expected to run.

46. The least number of points that will give satisfactory results is three, and if four or more are taken, the computations are probably correct if the points all lie on a smooth curve. More points should be taken if there is any doubt as to the shape of the curve within the working range. In the present design, assume successively for the armature flux per pole, 3,000,000, 3,500,000, and 4,000,000 lines. All the areas of the paths are known, and the densities, therefore,

are readily obtained by division. The flux in the armature core is half of the total flux per pole; that in the magnet cores and pole pieces is 1.14 times the armature flux per pole on account of magnetic leakage; and the flux in the yoke is half of that in the magnet cores. The ampere-turns per inch of length of path are taken from the curves in Fig. 41, Part 2, except in the case of air, which is computed after the manner already explained. The several quantities used in obtaining the total ampere-turns are shown in Table III.

47. These values are plotted in Fig. 11, and a smooth curve drawn through them. Now, the ampere-turns for the

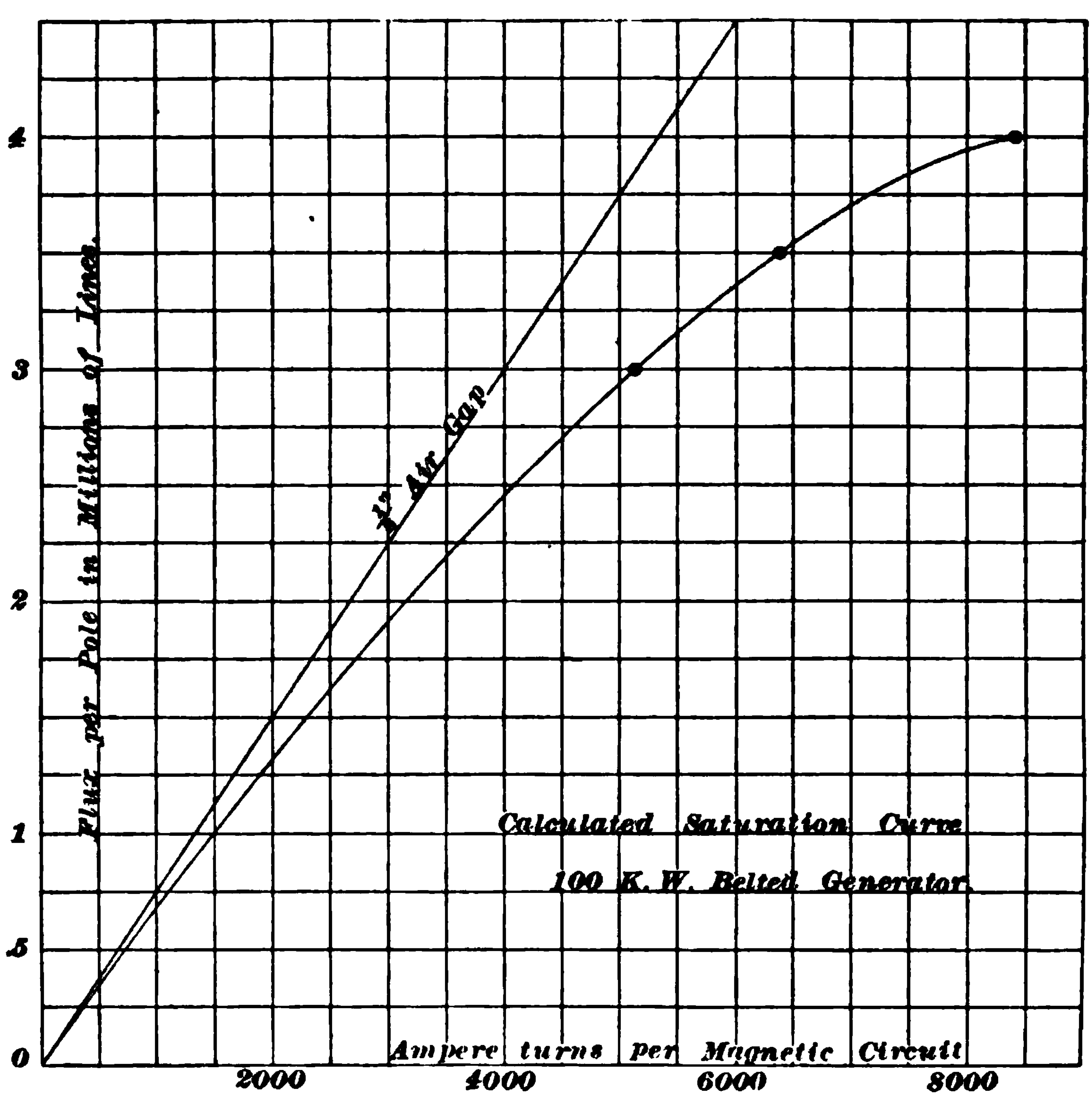


FIG. 11

air gap for the several values of the flux varies directly as the flux, because the length and area of the path are constant,

TABLE III

For an Armature Flux of 3,000,000 Lines Per Pole

Part	Flux	Area	Density	*I T* Per Inch	Length	Total *I T*
Armature core..	1,500,000	33.2	45,200	12	10	120
Teeth.	3,000,000	33.0	90,900	44	3½	154
Air gaps.... ...	3,000,000	58.7	51,100	$\frac{51,100}{3.192}$	¼	4,000
Pole pieces......	3,420,000	46.5	73,500	24	18	432
Yoke...........	1,710,000	30.0	57,000	20	22½	450
Total ampere-turns for 3,000,000 lines....................						5,156

For an Armature Flux of 3,500,000 Lines Per Pole

Path	Flux	Area	Density	*I T* Per Inch	Length	Total *I T*
Armature core..	1,750,000	33.2	52,700	14	10	140
Teeth	3,500,000	33.0	106,000	95	3½	333
Air gaps........	3,500,000	58.7	59,600	$\frac{59,600}{3.192}$	¼	4,667
Pole pieces......	3,990,000	46.5	85,800	35	18	630
Yoke...........	1,995,000	30.0	66,500	27	22½	608
Total ampere-turns for 3,500,000 lines....................						6,378

For an Armature Flux of 4,000,000 Lines Per Pole

Path	Flux	Area	Density	*I T* Per Inch	Length	Total *I T*
Armature core..	2,000,000	33.2	60,200	17	10	170
Teeth.	4,000,000	33.0	121,200	240	3½	840
Air gaps.......	4,000,000	58.7	68,200	$\frac{68,200}{3.192}$	¼	5,335
Pole pieces......	4,560,000	46.5	98,000	65	18	1,170
Yoke...........	2,280,000	30.0	76,000	40	22½	900
Total ampere-turns for 4,000,000 lines....................						8,415

as is also the permeability of air; therefore, if any value of the air-gap ampere-turns is plotted, say, for 4,000,000 lines, 5,335 ampere-turns, and a straight line drawn through this point and the origin *O*, all other values of the air-gap turns for various fluxes may be read from this line. In Fig. 11, then, the ampere-turns to the left of the air-gap line are those required for the air gap, and those to the right, between the total curve and the air-gap line, are the ampere-turns required for the iron part of the magnetic circuit. Now, at low densities, iron conducts magnetism very readily, and very few ampere-turns are required, so the magnetization curve for small fluxes approaches the air-gap line and is tangent to it at zero flux. In drawing the magnetization curve, then, it must pass through the points plotted and be tangent to the air-gap line.

48. When a saturation curve is obtained experimentally from the actual machine, it should be compared carefully with the calculated curves. Draw through the origin a tangent line for the air-gap line, and if this does not agree with that of the calculated curve, the method of estimating the area of the air gap should be modified in future calculations. If the ampere-turns for the iron in the calculated curve are not correct, the magnetization curves of the materials may be at fault, and samples of the materials should be tested and new curves made.

It is important that the magnetization curve of a dynamo be bent or curved, and this is accomplished by having some part or parts of the magnetic circuit magnetically saturated. If this is not done, a change in the ampere-turns will mean a corresponding change in the flux and voltage, and the latter becomes unstable; while, if saturation takes place, a change in the ampere-turns will cause but a small change in the flux and voltage, and the machine is said to be stable. A good rule to follow to insure stability is to so proportion the magnetic circuit that, at full load, from 25 to 35 per cent. of the ampere-turns is required for the iron. The full-load flux in the present design has been computed

as 3,860,000 lines, which require by the curve some 7,700 ampere-turns. For the air gap, 5,150 ampere-turns are required, leaving 2,550 ampere-turns for the iron, or about 33 per cent. of the total, 7,700 ampere-turns. This design should therefore be satisfactory as regards stability of voltage.

EFFECTS OF ARMATURE REACTION

49. Calculation of Cross Ampere-Turns. — Before taking up the design of the field windings, it is necessary to investigate the effects of armature reaction. The armature reaction depends on the load on the dynamo in kilowatts, and is the same for all three voltages, since the product of the total number of face conductors and the current in each is the same. The two effects of the armature reaction that are to be compensated for in the field windings are the back ampere-turns and the cross ampere-turns. These two have been shown to be equal, numerically, to the ampere conductors within the double angle of lead of the brushes, and to those beneath the pole faces, respectively. To predetermine the angle of lead of the brushes necessary to secure sparkless commutation is difficult, if not impossible, so the value of the back ampere-turns is usually unknown until the generator is tested. However, they are much less important than the cross ampere-turns, because they are usually much smaller in value than the latter. The cross ampere-turns are computed by the formula

$$\text{cross ampere-turns} = \frac{\% \times Zi}{p}$$

in which $\%$ = percentage of armature covered by poles;
Z = total number of face conductors;
i = current in each;
p = number of poles.

For the 500-volt armature, this is

$$\frac{.75 \times 464 \times 100}{6} = 5,800$$

50. Effect of Cross Ampere-Turns.—These ampere-turns tend to weaken one pole tip and strengthen the other to an equal degree. Referring to the table of ampere-turns for 4,000,000 lines flux per pole, which is about full-load flux, it is seen that there are 5,335 ampere-turns required for the air gap and 840 ampere-turns for the teeth, or a total of 6,175 ampere-turns, to maintain the flux across the air-gap region if it is evenly distributed. If the ampere-turns required to set up this cross-flux in the armature core and pole pieces be neglected, the ampere-turns under the weak pole tips will be $6,175 - 5,800 = 375$, while under the strong pole tips $6,175 + 5,800 = 11,975$ ampere-turns will be displayed. Now, the density in the air gap will be proportionally weakened at the weak pole tips, but on account of the teeth having already reached saturation, the strong pole tips cannot be strengthened proportionally. Not only are the teeth saturated, but the pole horn was carefully designed to be strongly saturated: and, further, the air gap at the tips of the poles is $\frac{3}{8}$ inch, while at the middle under the body of the pole it is but $\frac{1}{8}$ inch. Thus, in three ways, the cross ampere-turns are prevented from doubling the strength of field at the strong pole tips: (1) by saturation of the teeth, (2) by saturation of the pole horn, and (3) by increasing the air gap at the tips. Sometimes the punchings forming the pole pieces are made alternately long and short at the pole face, where magnetic saturation then takes place, and this has the same effect as saturation of the teeth. This method of constructing laminated poles is described later in connection with railway motors.

51. Compensation for Cross Ampere-Turns.—Now, the effect of all this choking by saturation and otherwise at the strong pole tip is to reduce the total flux, for the weakening effect of the cross ampere-turns is in no way prevented, while the strengthening effect is greatly interfered with. Thus, the cross ampere-turns tend to reduce the flux just the same as do the back ampere-turns, and in order to prevent the flux from being lessened, due to

either effect, the machine should be provided with series-coils on the field magnets, that is to say, coils that are connected in series with the armature and through which all the current developed by the armature passes. Now, the armature reaction depends on the armature current, and since these series-turns are supplied with the same current, it is evident that by properly proportioning the number of turns in these series-coils, they may be made to satisfactorily compensate for both the back and cross ampere-turns.

52. But these are not all the advantages to be derived from the saturation of the teeth, pole tips, etc. It was shown that, under the weak pole tips at full load, had there been no series ampere-turns added, only some 375 ampere-turns are impressed, against 6,175 ampere-turns at no load, so the strength of field would be practically zero. Now, a very weak field at this point is undesirable, making it necessary to rock the brushes far ahead to get the coils, under commutation, into the magnetic fringe of the pole, and thus assist in the reversal of the armature currents, as has been explained. The addition of ampere-turns on the field magnets by means of series-coils, which ampere-turns increase as the machine is loaded, cannot much affect the strong side of the pole that is already saturated, and the result is that the additional flux must find a path through the weak side of the pole. Consequently, the weaker side of the pole is greatly strengthened, and, instead of having one side very weak and the other very strong, as would have been the case without any magnetic saturation in the region near the air gap, a fairly good distribution of the flux over the pole face is obtained. While this is by no means a uniform distribution, yet it is sufficiently near to it to be quite satisfactory.

53. The saturation of the teeth, pole tips, and pole face, and the lengthening of the air gap under the tips, constitute the chief methods in use for overcoming armature reactions.

They are incorporated in practically all modern generators, although some of these may have, in addition, some patented scheme for balancing the magnetic effects of the armature. The foregoing explanation of the action of the dynamo under load should be carefully gone over until thoroughly understood by the student and should be compared with the former explanations of armature reaction. It will be noted that, in designs wherein saturation of the iron at or near the air gaps is used for preventing the undesirable effects of the armature reaction, many more series ampere-turns are needed than in designs where no such saturation takes place. Therefore, it follows that the former type is quite undesirable for shunt-wound generators, because the voltage would fall off as the machine is loaded, on account of the choking of the flux at the strong pole tips, while the latter type, to which belonged most of the earlier designs of dynamos, operated quite satisfactorily as shunt-wound machines.

54. Ampere-Turns to Offset Armature Reaction. From the foregoing discussion of armature reaction, it should be evident that the matter is too complex to compute the number of ampere-turns necessary to add as series ampere-turns to compensate for saturation. It is known, at least, however, that they should be proportional to the armature ampere-turns, and from tests it has been found that, to compensate for both the cross and back ampere-turns, from 20 per cent. to 50 per cent. of the armature ampere-turns should be added to the series-coils of each magnetic circuit, the value depending on the degree to which the saturation is carried. In the design at hand, the armature ampere-turns are, from the equation, armature $I\,T = \frac{Z\,i}{p} = \frac{464 \times 100}{6} = 7{,}730$ ampere-turns for the 500-volt windings. Supposing that 40 per cent. of these are allowed for armature reaction; then, about 3,100 ampere-turns will be required on the series-coils to compensate for the cross and back ampere-turns.

CALCULATION OF FIELD WINDING FOR 115-125 VOLTS

55. For the purpose of illustrating the methods of calculating the field windings, let it be desired to wind a machine to give 115 volts at no load and 125 volts at full load, using the armature winding already determined for 125 volts. The variation of the voltage with the load is to be automatic, that is to say, the field-regulating rheostat is not to be adjusted. At no load, since there is no current flowing, there will be no resistance drop in the windings, so if 115 volts is developed in the armature, there will be 115 volts at the terminals. However, at full load there will be required about 8 volts to force the current through the windings; so, in order to obtain 125 volts at the terminals, about 133 volts must be developed in the armature windings. The flux per pole Φ for no load is

$$\Phi = \frac{E \times 10^8 \times 60 \times m}{Z \times S \times p} = \frac{115 \times 10^8 \times 60 \times 6}{348 \times 575 \times 6}$$

$$= 3,450,000 \text{ lines approximately}$$

At full load the flux should be $\frac{133 \text{ volts}}{115 \text{ volts}} \times 3,450,000$ $= 3,990,000$ lines per pole, because the voltage is directly proportional to the flux, the speed remaining constant.

From the magnetization curve, Fig. 11, for 3,450,000 lines per pole, it is seen that 6,120 ampere-turns are required per magnetic circuit, and for 3,990,000 lines per pole, 8,200 ampere-turns are required. Now at no load there is no current in the series-coils, so the shunt coils must be wound to develop the 6,120 ampere-turns. The regulating rheostat is adjusted to make the shunt current such that 6,120 ampere-turns are developed at no load with 115 volts at the terminals of the shunt circuit. Now, when the machine is under full load, the terminal voltage is to be raised to 125 volts, so the shunt current will increase in the ratio $\frac{125}{115}$, and so will the ampere-turns developed by this

current So the shunt ampere-turns at full load then are $\frac{125}{115} \times 6{,}120 = 6{,}650$, approximately.

At full load, 8,200 ampere-turns are required per magnetic circuit without allowing for armature reaction, and 3,100 are needed to compensate for the latter, so that at full load the total ampere-turns on each magnetic circuit is 11,300. Of this, the shunt coils develop 6,650, so the series-coils must then develop the remainder, or 4,650.

Referring to the diagram of the magnetic circuit, Fig. 5, it will be noticed that there are two sets of field coils on each circuit, so that each of the six shunt coils should develop 3,325 ampere-turns and each of the six series-coils 2,325 ampere-turns at full load.

56. Series-Winding. — Taking up first the series-coils, the current for 100 kilowatts at 125 volts is $\frac{100000}{125} = 800$ amperes, so that each turn on the series-coils develops 800 ampere-turns; hence, there will be required $\frac{2325}{800}$, or 2.9 turns per coil. It is impossible to have a fraction of a turn of wire, so far as magnetic effects are concerned, for it is either a turn or not a turn. No matter what the direction of winding, these coils must alternate, since the poles alternate in sign, and the result of this is to divide the effect of one turn between two adjacent poles, so that it is usually stated that the turns per pole are $2\frac{1}{2}$, $3\frac{1}{2}$, or $4\frac{1}{2}$, etc. Fig. 12 shows a winding of $1\frac{1}{2}$ turns per pole. It will be noticed that between every two magnet cores, there pass three conductors *a*, *b*, and *c*, or *1*, *2*, and *3*, with the current in them in the same direction. This winding, therefore, has 3 turns per magnetic circuit, or 3 turns for two poles, but is usually said to have $1\frac{1}{2}$ turns per pole.

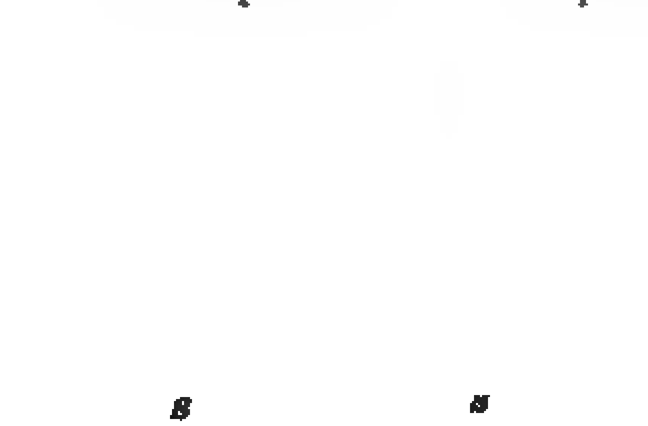


FIG. 12

57. In the design, 2.9 turns per coil are required, and there is the choice, therefore, between 2½ and 3½ turns on alternate poles, averaging 3 turns per pole, or of putting 3½ turns per pole and placing a shunt across the terminals of the series-coils to divert a part of the 800 amperes and thus reducing the series ampere-turns to any desired degree. Since the terminals of the series-coil must come out at opposite sides, it is not practicable to use 3 turns per coil; the terminal must be brought around to the other side, thus making 3½ turns.

From similar designs, where the depth of the winding is not too great, about 1,200 circular mils per ampere has been found to give coils that will not heat over 40° C. above the temperature of the surrounding atmosphere; 800 amperes at 1,200 circular mils will require 960,000 circular mils, or 960,000 × .7854 = 753,900 square mils, approximately, or about ¾ square inch in section. In the diagram, Fig. 5, 2 inches has been assumed for the depth of the space for the coil. Allowing ¼ inch under and over coils for clearance and insulation leaves 1½ inches for the depth of the winding. We will use, then, a copper strip ½ in. × 1½ in. bent on edge.

58. For the winding room along the magnet core, it is necessary to count on the next greater number of turns, or 4 turns. The conductor should be tapped with ¾-inch half-lapped tape, and, allowing .05 inch for insulation, this makes the conductor .55 in. × 1.55 in. over all. Four turns along the core would require 2.2 inches or about 2¼ inches for the conductor only; but there must also be left room for the connecting leads from coil to coil. If ¼ inch is allowed for each of these, the net length of the winding becomes 2¾ inches. Allowing $\frac{1}{16}$ inch for insulation under binding, and ⅛ inch for the diameter of the binding cord, adds $\frac{3}{16}$ inch on a side, or ⅜ inch over all, so the total length of the series-coil along the core is 3⅛ inches.

59. Shunt Winding.—The size of wire for the shunt winding is determined from the formula

$$\text{circular mils} = \frac{i\,T \times L}{e}$$

in which $i\,T$ = ampere-turns per coil;
L = mean length of a turn in inches;
e = volts at the terminals.

The ampere-turns required per coil are 3,325. The mean length of a turn may be estimated from Fig. 13. Allowing $\frac{1}{4}$ inch all around the pole piece, which is 7 in. × 7 in., makes the length of the shortest turn about $7\frac{1}{2} \times 4 = 30$ inches. The outside turn will be longer than the inside by a circumference of a circle whose radius is the depth of winding, say $1\frac{1}{2}$ inches. The circumference of a circle of $1\frac{1}{2}$ inches radius is 9.4 inches or $9\frac{1}{2}$ inches, so the length of the greatest turn is $39\frac{1}{2}$ inches. The mean length between the shortest and the greatest is $\frac{30 + 39\frac{1}{2}}{2} = 34\frac{3}{4}$ inches. The voltage at the terminals of each coil, since the shunt coils are connected in series, is one-sixth of the voltage across all the coils. In the shunt circuit, a regulating rheostat should be included, having a resistance to take up about 20 per cent. of the full-load voltage of the machine, leaving 80 per cent. for the coils. $.80 \times 125 = 100$ volts for all coils, so that at the terminals of each coil there will be $\frac{100}{6} = 16.666$ volts.

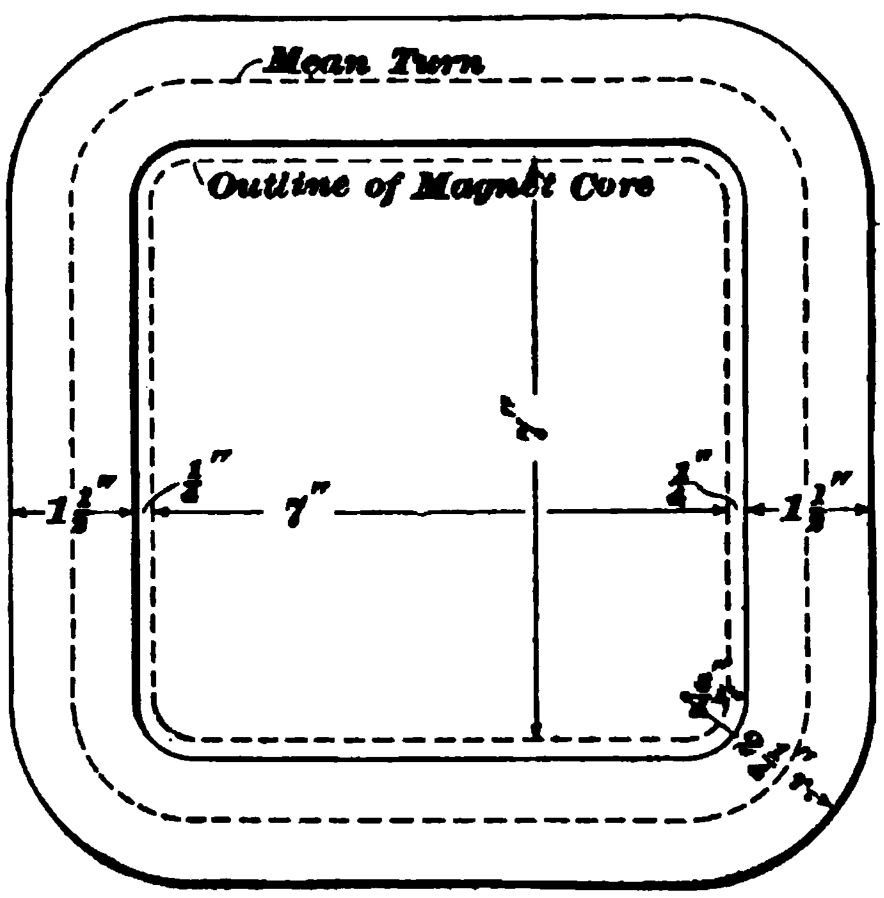


FIG. 13

Each shunt coil, then, must develop 3,325 ampere-turns with a terminal pressure of 16.666 volts and a mean length of turn of $34\frac{3}{4}$ inches. We have, then, circular mils $= \frac{3,325 \times 34.75}{16.666} = 6,933$ circular mils. Referring to the wire table, it will be seen that No. 11 B. & S. wire

has an area of 8,234 circular mils, and No. 12 B. & S. wire has an area of 6,530 circular mils. If no other sizes of wire than those of the B. & S. gauge are at hand, the coils could be wound with both sizes in such proportion as to bring the average circular mils, including the quantity of each size used, to the required value. If the coils in this case were wound entirely with No. 12 B. & S. wire, the voltage at the terminals of the coils would have to be somewhat greater than $16\frac{2}{3}$ volts. How much greater is readily determined by solving the equation, circular mils $= \frac{i\,T \times L}{e}$, for voltage; thus: $e = \frac{i\,T \times L}{\text{cir. mils}} = \frac{3{,}325 \times 34.75}{6{,}530} = 17.7$ volts; so for the six coils in series, 106.2 volts would be required. This would leave $125 - 106.2 = 18.8$ volts for the rheostat. This is sufficient for regulating the voltage, and a winding of No. 12 B. & S. wire will therefore be used.

60. The field wire has an area of 6,530 circular mils, so at 1,200 circular mils per ampere, the permissible current is $\frac{6530}{1200} = 5.4$ amperes, approximately, in the shunt circuit. With a current of 5.4 amperes the turns required per coil will be $\frac{3{,}325}{5.4} = 616$, in order to give 3,325 ampere-turns.

The length of the winding space allowed on the sketch, Fig. 5, is 7 inches for both coils, and the series-coil has been found to require $3\frac{1}{8}$ inches of this, leaving $3\frac{7}{8}$ inches for the shunt coils. Allowing, as in the case of the series-coils, $\frac{3}{16}$ inch on a side for insulation and cord, or $\frac{3}{8}$ inch for both sides, leaves $3\frac{1}{2}$ inches for the net winding space. A single cotton covering on the wire will be sufficient for these coils, and from the wire table we find that No. 12 B. & S., S. C. C. has a diameter of .087 inch. A layer of this $3\frac{1}{2}$ inches wide should have 40 turns, or, say, 38 turns per layer in order to allow for clearance. Seventeen such layers would make a total of 646 turns per coil. The depth of the winding is $17 \times .087 = 1.48$ inches, which is very nearly the same as that for the series-coils. If the depth of winding is

considered too shallow, the winding space should be shortened, making the diameter of the yoke less, while if it is too deep, the winding space must be lengthened.

61. In the same manner, the field coils for any other voltage or any other compounding desired may be computed. The flux per pole at full load should always be about the same for a certain magnet frame, regardless of the compounding, so if it is desired to compound a generator for as great a rise as say 15 per cent. at full load, it is accomplished by lowering the flux at no load to a proper value rather than raising the flux at full load, and then selecting a suitable armature winding to give the voltage wanted at the required speed.

THE MECHANICAL DESIGN

SUMMARY OF DIMENSIONS

62. The electrical design of the machine is complete, but the mechanical design still remains to be worked out. For convenience in referring to the quantities already determined that are involved in the mechanical design, the following data are given:

Generator, 100 kilowatts; output 125, 250, 500 volts; 575 revolutions per minute; belted type; 6 poles.

Armature. — Diameter of armature 27 inches outside, 11 inches inside; length of armature, $6\frac{3}{4}$ inches with one $\frac{1}{2}$-inch air flue; number of slots, 58; size of slots, .51 in. × $1\frac{3}{4}$ in., with a $\frac{3}{16}$-inch wedge in top for retaining winding in place.

Armature Winding, 125 Volts.—Single parallel winding, one turn per coil, with four cross connecting rings; three coils per slot; 174 coils; coils span 10 slots; armature conductor, .10 in. × $\frac{5}{8}$ in.

Commutator, 125 Volts.—Nineteen inches diameter; face sufficient for six $\frac{7}{8}'' \times 1\frac{3}{4}''$ brushes per set; 174 segments; coils connect to adjacent segments.

Armature Winding, 250 Volts.—Double series-windings, one turn per coil; four coils per slot; 232 coils; coils span 10 slots; armature conductor, .075 in. × $\frac{5}{8}$ in.

Commutator, 250 Volts.—Nineteen inches diameter; face sufficient for four $\frac{5}{8}'' \times 1\frac{3}{4}''$ carbons per set; 232 segments; coils span 78 segments.

Armature Winding, 500 Volts.—Same as for 250 volts, but a *single* series-winding.

Commutator, 500 Volts.—Nineteen inches diameter; face sufficient for three $\frac{7}{16}'' \times 1\frac{3}{4}''$ carbons per set; coils span 77 segments.

Poles.—Laminated iron; length, 7 inches, with $\frac{3}{8}$-inch end plates; bore of poles, $27\frac{1}{4}$ inches; angular span of poles, 45°.

Magnet Cores.—Section, 7 inches square; winding room for field windings, 7 inches long by 2 inches deep.

Yoke.—Cast steel; area of section, 30 square inches.

DESIGN OF ARMATURE AND COMMUTATOR

63. The armatures for the three voltages will differ only in the length of the face of the commutators, and for convenience only that for 250 volts will be shown. The armature will be designed with a spider upon which the commutator is supported, so that the whole may be made complete without the shaft, as is desirable for engine-type machines.

64. Shaft and Spider.—The diameter of the shaft may be approximated from the formula already given,

$$\text{diameter} = k\sqrt[4]{\frac{\text{watts}}{\text{R. P. M.}}}$$

For 100 kilowatts, k is 1.2, so that

$$d = 1.2\sqrt[4]{\frac{100{,}000}{575}} = 4.36, \text{ or, say, } 4\tfrac{1}{2} \text{ inches}$$

The hub of the spider should be heavy enough to withstand the bursting strains when pressed on the shaft with an

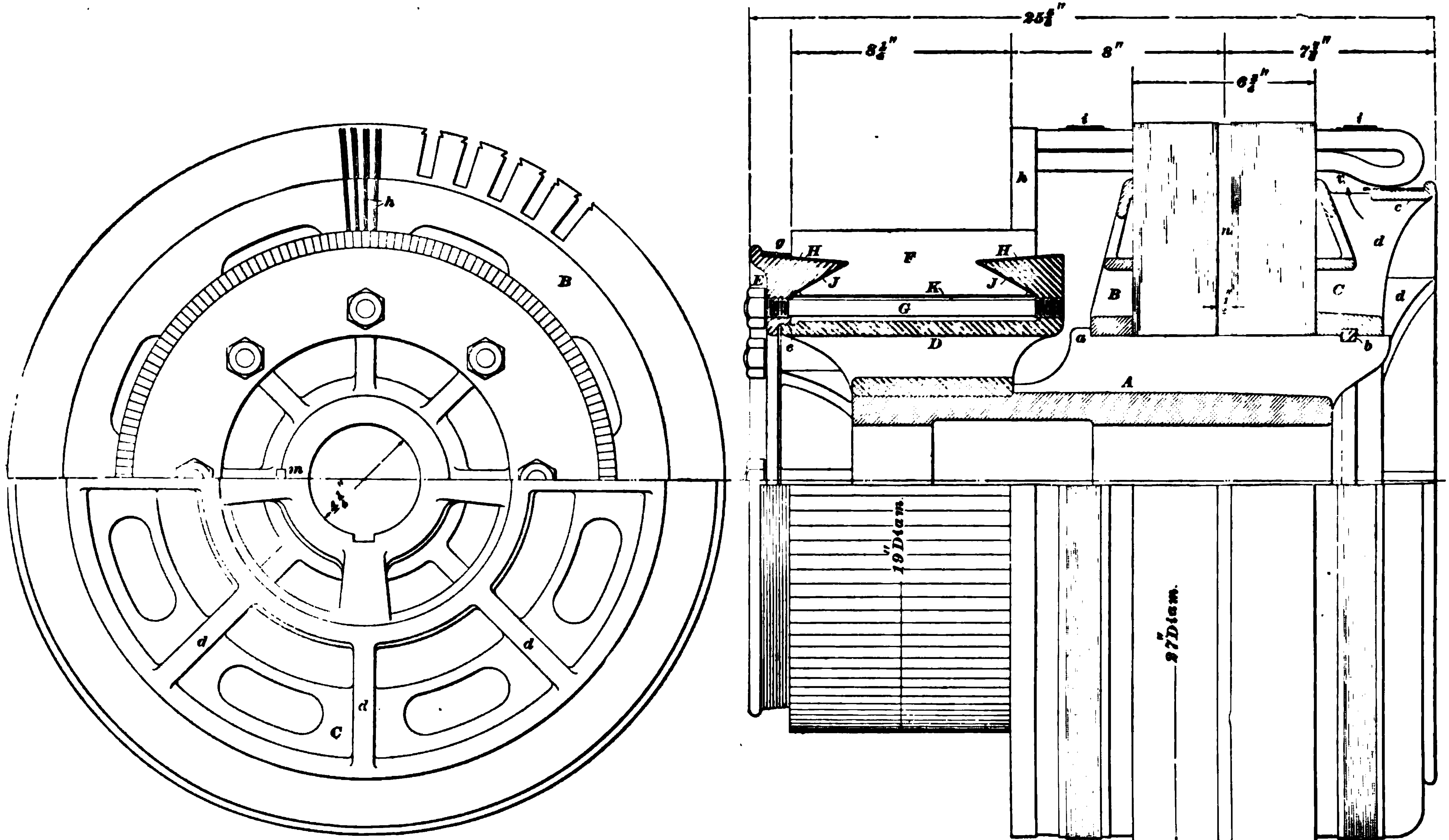


FIG. 14

hydraulic press. Supposing we use four arms about 2 inches thick for supporting the armature core, in one of which arms a key is inserted that fits into a nick in the punchings to prevent them from turning on the spider. Provision must be made for clamping the punchings together, and the method to be used will be plainly seen from the section of the armature shown in Fig. 14. The upper half of the end view shows the armature looking toward the commutator end; the lower half shows the view looking toward the back of the armature. The front and rear end plates *B* and *C* are entirely separate from the spider *A*. The front end plate *B* strikes against a slight projection *a* on the spider arms, while the rear end plate *C* is keyed on by a small square key *b*, bent into the form of a ring that fits into grooves cut in the spider arm and end plate. This key is made in two pieces, in order to insert it properly; the joints are usually arranged at the spider arms, and are not seen in the completed armature. The punchings, of course, have a considerable spring, and when assembled on the core are clamped in a press, the key *b* inserted and the pressure released. The end plate *C* will then be pushed back and clamp the key tightly.

The front end plate *B*, as shown in Fig. 14, consists of a circular casting cored out and ribbed so as to obtain maximum stiffness for the least weight.

65. Sometimes the front end plate is provided with flanges for supporting the winding, as shown for the rear plate *C* in Fig. 14, but in the present case the winding is made of heavy rectangular copper bars, and their stiffness, together with the support given by the necks *h* of the commutator segments, will be sufficient to properly support the winding. The rear end plate *C* is much the same design as *B*, except that the flange *c* for supporting the winding is added. This flange is in turn supported by the eight arms *d*, as shown in the rear end view. It will be noticed that in Fig. 14 there are provided very ample passages *v* up through the windings on the ends, and the arms *d* serve to fan air

through these while running, and materially aid in cooling the armature. The distance the windings will project beyond the core is determined usually by making a careful drawing of the coils developed out into a plane instead of on a cylinder. The coils each span ten slots, so the end connections from the core to the bend at the rear end should advance through five slots and another five in returning from the bend to the core. At the front end the advance on each commutator lead should be about five slots also, and the distance from the core to the commutator necks therefore should be about the same as that allowed for the end connections on the rear end.

66. The ventilating flue *n* is formed by putting in a spacing disk, Fig. 15, consisting of an armature punching to

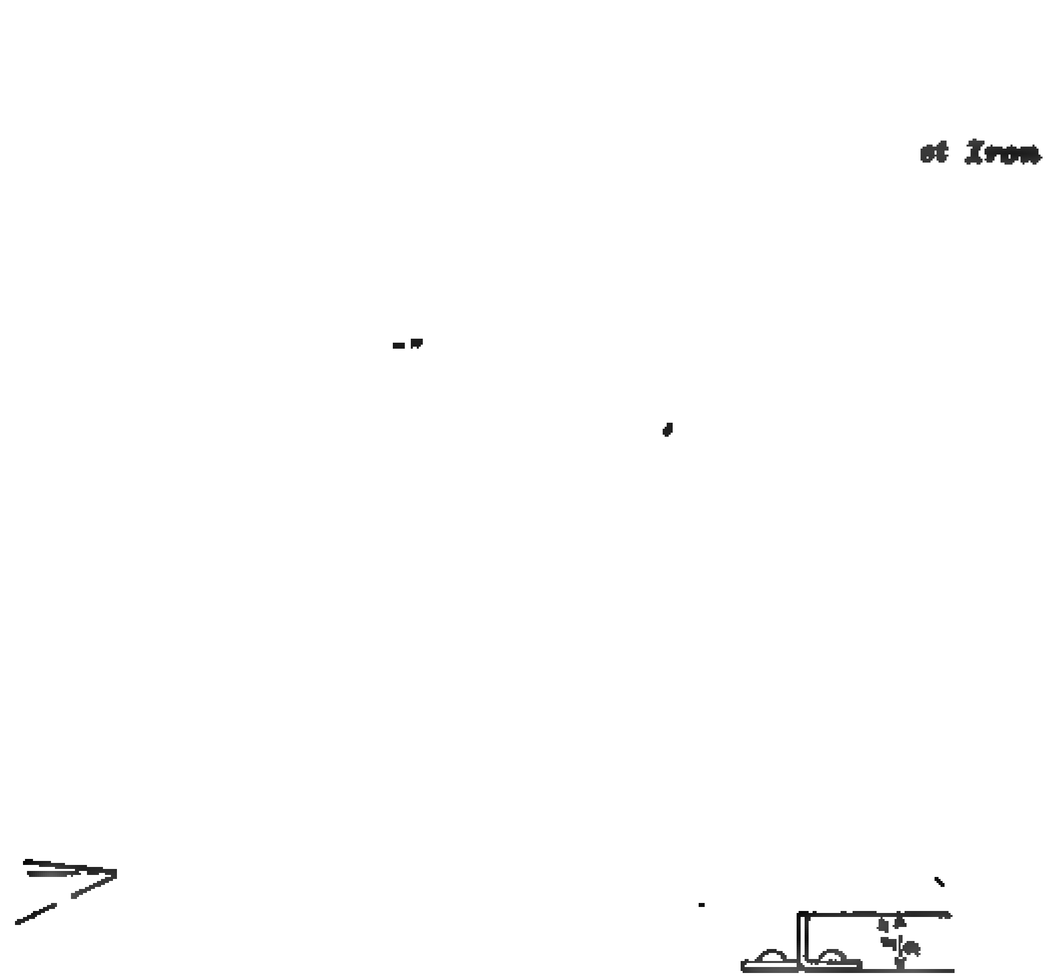


FIG. 15

which sheet-iron strips have been riveted, as shown. These strips are ⅛ inch wide, the width of the ventilating flue, and

have two projections that are bent at right angles, one right and one left, thus forming feet by means of which the strips are held on edge. Through these feet small rivets pass for attaching the strip to the armature punching.

67. The hub of the armature spider projects on the front end and is turned off to receive the commutator. This last consists of a spider or shell D and a clamping ring E arranged to hold the segments F between them. Both D and E are made of cast steel, as great strength is required to hold the segments tightly. The spider D is arranged with eight arms, leaving passages through which air can circulate between the commutator and the hub of the armature spider. The commutator is one of the most expensive parts of the dynamo, and is therefore made as small as practicable; this results in there being so little surface to radiate the heat developed that the temperature rise is usually greater here than on any other part of the machine. The ventilation of the commutator spider will materially decrease the temperature rise. The front end of the spider is turned off at e and the wedge ring is turned to fit this, as shown, the two parts being clamped together by the eight bolts G. These bolts are turned to a smaller diameter in the middle in order that there shall be considerable give to allow for the unequal expansion of the segments and the shell when heated. A suitable lock washer is held beneath the nuts of the clamping bolts to prevent them from loosening.

68. In Fig. 16 is shown a detail of the commutator segment. This consists of a hard-drawn copper bar F to which is riveted a neck h suitably arranged to receive the two ends of armature coils that terminate in the segment. The commutator should have sufficient face to accommodate four $1\frac{3}{4}$-inch brushes. Allowing $\frac{5}{32}$ inch between carbons, and $\frac{5}{32}$ inch for staggering the brushes, we have $(4 \times 1\frac{3}{4}) + (4 \times \frac{5}{32}) = 7\frac{5}{8}$ inches as the actual working face of the commutator. Allowing $\frac{3}{8}$ inch extra on the inside and $\frac{1}{4}$ inch outside, makes up the length $8\frac{1}{4}$ inches, as shown. Where

the brushes do not butt against one another, that is, where there is a space between the carbons, the wear of the

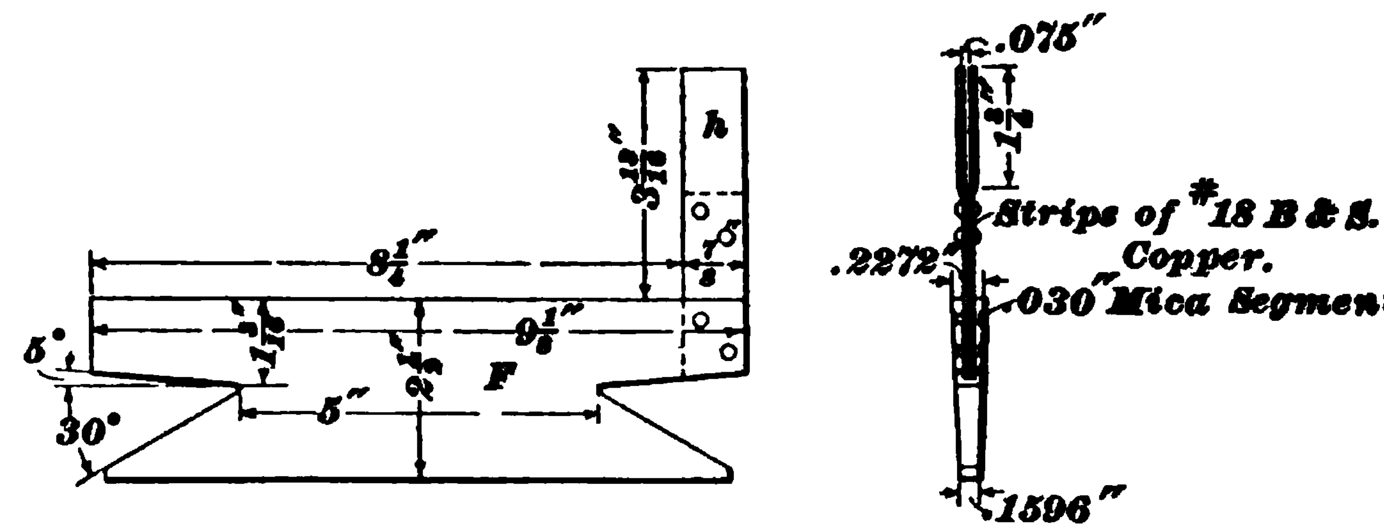


FIG. 16

carbons is liable to leave a ridge on the commutator between brushes, which may eventually necessitate turning the commutator in a lathe. To avoid this difficulty, the brushes of one brush-holder stud are placed out of line with those of the next stud in such a manner as to wear away any ridge that may be left by the first set. When brushes are so set they are said to be staggered.

69. The segments should have sufficient depth to allow for $\frac{3}{4}$-inch wear, measured radially, so the point of the **V** cut should be, say, $1\frac{3}{16}$ inches below the face. Using the angles 5° and 30°, as shown, requires that the segments be about $2\frac{1}{2}$ inches deep. The diameter at the surface is 19 inches, and there are 232 bars, so the thickness of one segment of copper and one of mica should be $\frac{3.1416 \times 19}{232}$ $= .2572$ inch. Taking the mica segment as .030 inch thick, leaves .2272 inch for the thickness of the copper. The diameter of the segments at the bottom is 14 inches, so the thickness of one mica and one copper segment is $\frac{3.1416 \times 14}{232} = .1896$ inch. Taking from this the thickness of the mica segment leaves for the copper .1596 inch, as shown. The copper is first drawn into bars of the proper section, then roughly cut to shape, after which they are milled to receive the neck h, which is both riveted and soldered into the ends of the segments.

70. In assembling the commutator, the proper number of segments, with mica segments between, are held tightly together by clamps around the outside; then the **V** grooves are turned carefully to size. The micanite sleeve *K*, Fig. 14, and the micanite cones *H* and *J*, are built up of thin leaves of mica pasted together with shellac or other varnish. These should be $\frac{1}{8}$ inch thick and made carefully to size. After the commutator is assembled, cord, shown at *g*, is wound over the mica cone on the outside end to protect it from injury. It is quite necessary that the insulating cones extend a considerable distance beyond the segments, for otherwise an accumulation of dust is liable to form a path for current over the mica, and the insulation between the windings and the frame of the machine will become impaired.

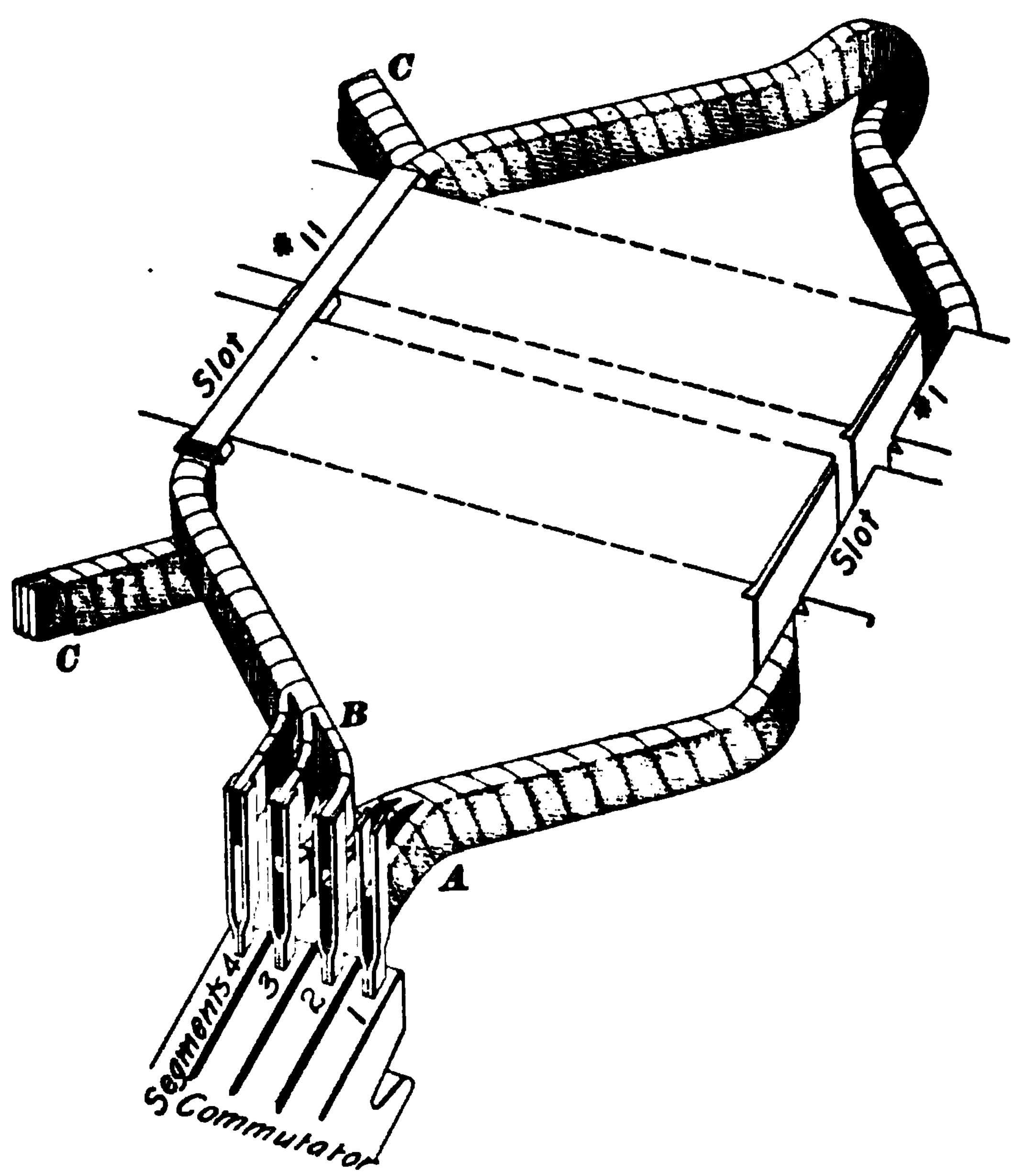


FIG. 17

71. The commutator having been completed, it is forced on the armature spider, and is kept from turning by a key shown at *m*, Fig. 14. The armature is now ready to receive

the winding. For 125 volts, the winding is of the parallel type, with three coils per slot, a set of coils for one slot being shown in Fig. 17. In the diagram, the armature core is, for simplicity, shown as straight instead of circular. The coils span 10 slots, that is, they lie in slots *1* and *11*, the lower side *A* being in slot *1*, the upper side *B* in slot *11*. Beneath *B* is the bottom side of some other coil *C*, and in the completed armature, each slot will have a set of conductors in the top and a set in the bottom. At the end *A* the three conductors spread out and are connected to the segments *1*, *2*, and *3*, while the ends *B* connect to the segments *2*, *3*, and *4*, so that coil *1* begins at segment *1* and ends at segment *2*. It will thus be seen that each coil terminates in adjacent segments, which is the essential feature of the single parallel winding.

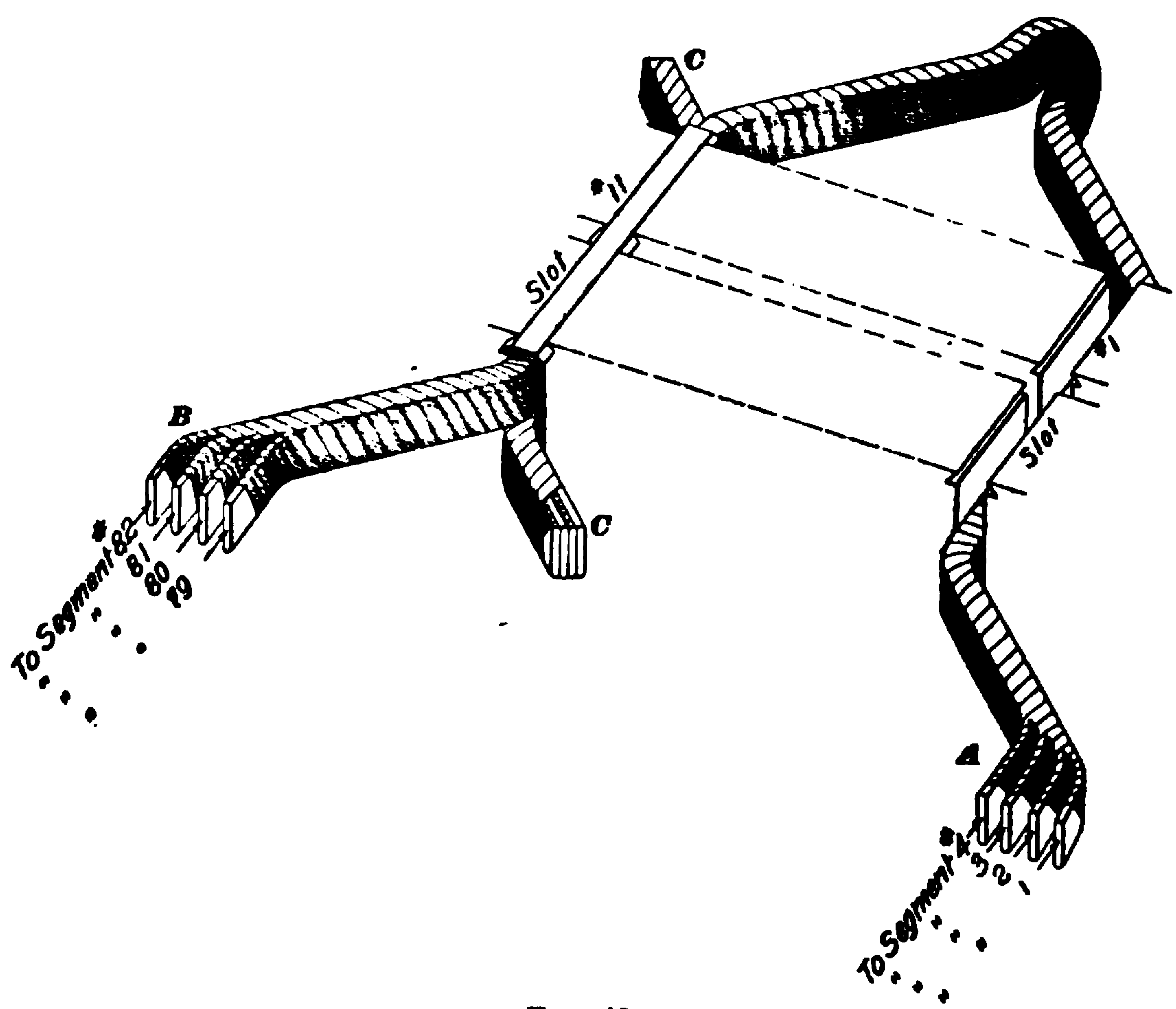


FIG. 18

72. For 250 and 500 volts, the armature coils are of the series-type, and have the appearance indicated in the diagram, Fig. 18; in this winding there are four coils per slot

taped together, and, as before, they span 10 slots. The necks of the commutator segments are omitted in order to avoid confusion, but it will be understood that the ends *A* go into the lower part of the necks and the ends *B* in the upper part of the necks, in the same manner as before. In the diagram, which is for the 250-volt winding, coil *1* connects from segment *1* to segment *79*, spanning 78 segments. From segment *79*, another coil connects, spanning 78 more segments, and terminating in segment *157*; another coil connects this to segment $157 + 78 = 235$, or, since there are but 232 segments in the commutator, segment 235 is segment *3*. Thus, a series of $\frac{p}{2}$, or three coils, p being the number of poles, extends around the commutator, terminating in segments *1* and *3* or in segments adjacent but one, which is the distinguishing feature of the double series-winding.

73. For 500 volts, the coils are very similar to Fig. 18, but should span only 77 segments, so that the ends at *B* should be marked to segments *78*, *79*, *80*, and *81*, instead of *79*, *80*, *81*, and *82*, as shown. If each coil spans 77 segments, a series of three would span 231, or starting at segment *1*, would terminate in segment *232*, which is adjacent to segment *1*.. This, then, would be a single series-winding.

CONSTRUCTION OF FIELD FRAME AND FIELD COILS

74. The field frame shown in Fig. 19 is divided horizontally into two parts for convenience in assembling or repairing the generator. It will be noticed that the area of the section of the yoke is greater than the calculated value required. It is frequently found necessary to considerably increase the area of a cast-steel yoke over that required for the magnetic flux, on account of the section being too small to be sufficiently stiff to withstand the powerful pull of the magnets. If the frame springs any, the length of the air gap at the various poles becomes unequal, and the strength of these

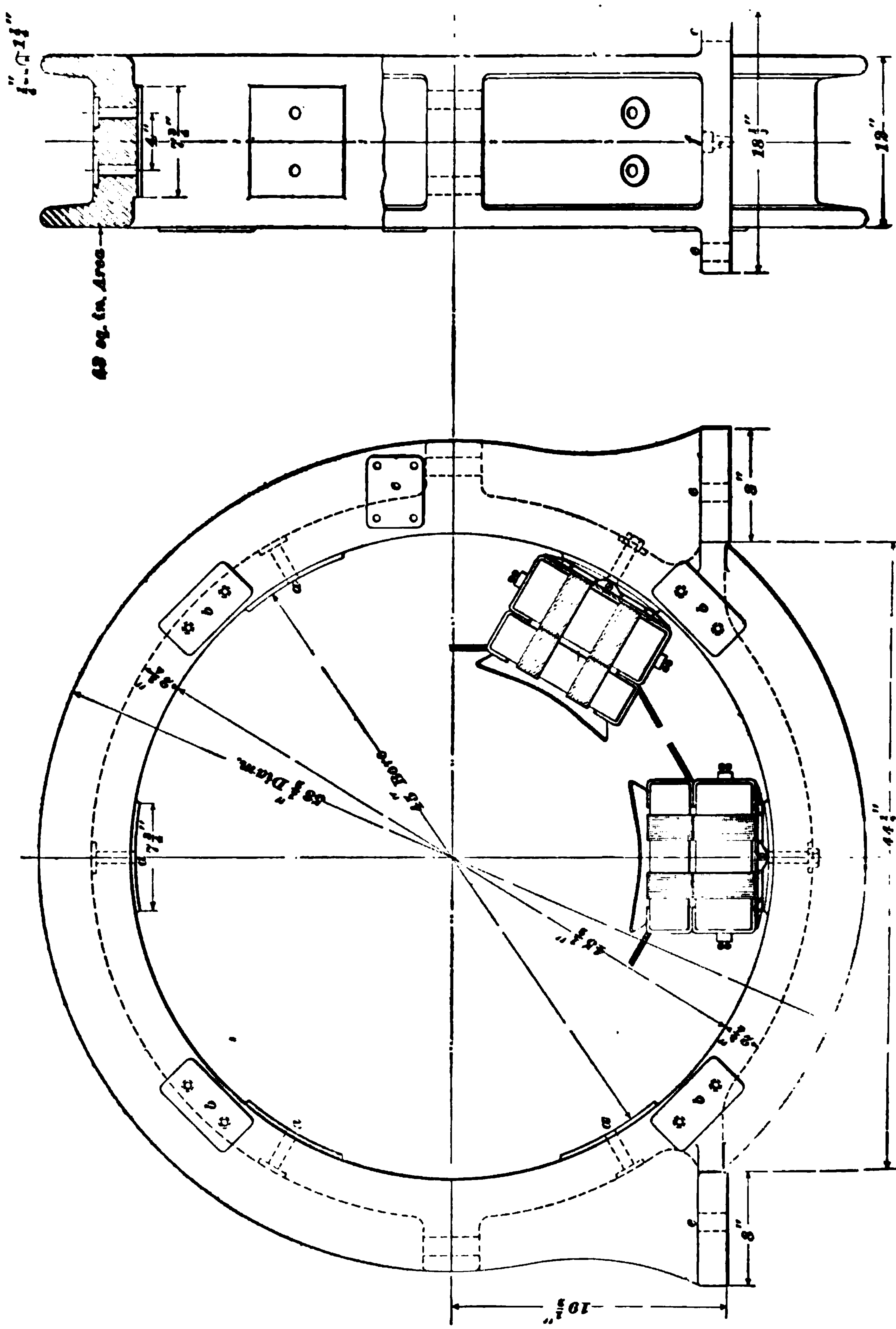


FIG. 19

poles is then affected so as to tend to distort the yoke still further out of shape. In the present case, the density assumed for the yoke calls for a cross-section of 30 square inches. This would make a rather light frame, and the section shown in Fig. 19 has an area of about 43 square inches, which would be better for a machine of this size, simply on account of the mechanical considerations just mentioned. This increase in the yoke section will not affect the field windings appreciably. The cross-section has been increased a little over 40 per cent. The yoke was originally calculated for a density of 75,000, so that the density with the increased cross-section would be about $\frac{30}{43} \times 75{,}000 = 52{,}326$. The ampere-turns required for the yoke are only about 10 per cent. of the total ampere-turns, and a reduction of the yoke density from 75,000 to 52,326 would correspond to a reduction of not more than 3 per cent. in the total ampere-turns. A change of one size in the shunt wire means a change of over 20 per cent. in the total ampere-turns, so that it is easily seen that the increase in the yoke section does not call for a recalculation of the magnetic circuit. The yoke density is comparatively low, so that an increase of cross-section has comparatively little influence on the field windings.

75. On the inside of the yoke are shown six pads *a* that are to be machined off to receive the pole pieces that are to be bolted to the yoke by two tap bolts, as shown. Two poles with their magnetizing coils are shown in place. On the front side of the yoke are shown four pads *b* that are to be machined off to receive four brackets for supporting the rocker-arm, details of which will be shown later. A pad *c* on the upper half is for attaching an adjusting screw by means of which the position of the brushes can be changed. In order to allow a little more room for the field coils, the bore of the pole-piece seats *a* has been increased to 45 inches, the inside diameter of the yoke to 45½ inches, and the outside diameter to 58½ inches. These dimensions are ¼ inch greater than those taken in Fig. 5, but this slight change will not affect the magnetic calculations perceptibly.

In each of the two feet are shown two holes *e* for bolts for attaching the yoke to the bedplate. In addition to these, there is a single hole *f* in each, for a taper pin. In assembling the machine, after the correct position of the yoke on the bedplate has been found, the bolts are tightened and the taper pin adjusted carefully and accurately into place. If the machine is taken apart, when it is reassembled the taper pins are inserted and driven into place first, and then the bolts put in and screwed up. By this means the yoke will be made to take its correct position on the bedplate without any other adjusting.

76. The details of the pole pieces are shown in Fig. 20. They consist of punchings $\frac{1}{32}$ inch thick, riveted between

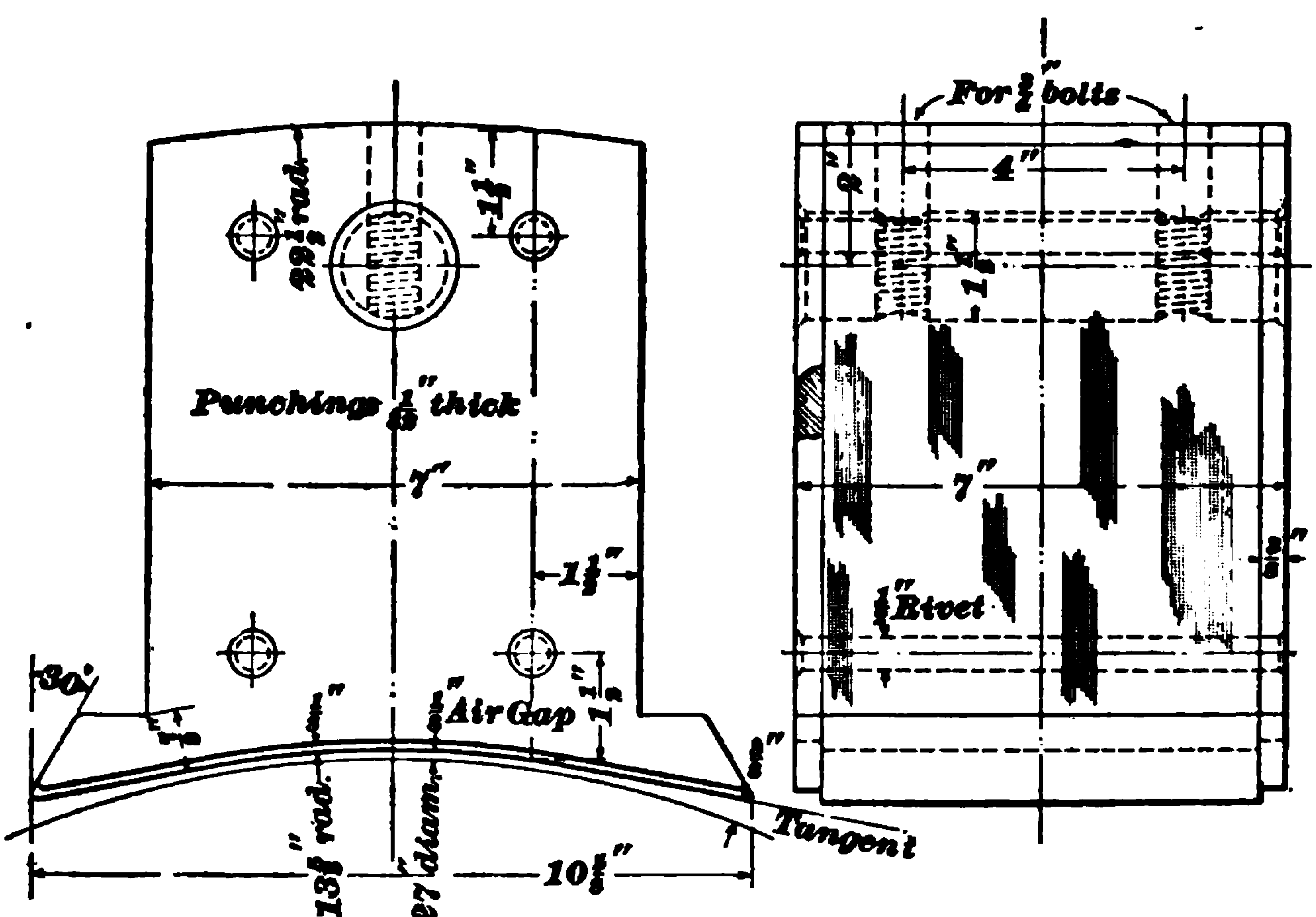


Fig. 20

two $\frac{3}{8}$-inch wrought-iron plates by five rivets. One of these is $1\frac{1}{8}$ inches in diameter, and this is drilled and tapped for two $\frac{3}{4}$-inch bolts that serve to hold the pole pieces to the yoke. The corners of the end plates should be carefully rounded, so that the insulation of the field coils will not be injured by the sharp edges.

77. In Fig. 21 the details of the field coils are shown. Both shunt coils and series-coils are wound on forms to leave $7\frac{1}{4}$ inches clear inside each way, the corners being bent to a radius of $\frac{3}{4}$ inch, as called for in Fig. 13. The field windings for 125 volts are shown, as these only have been computed, but the coils will remain practically the same size for whatever voltage is used. The shunt coil is wound with No. 12 B. & S. single cotton-covered wire, with 38 turns in a layer,

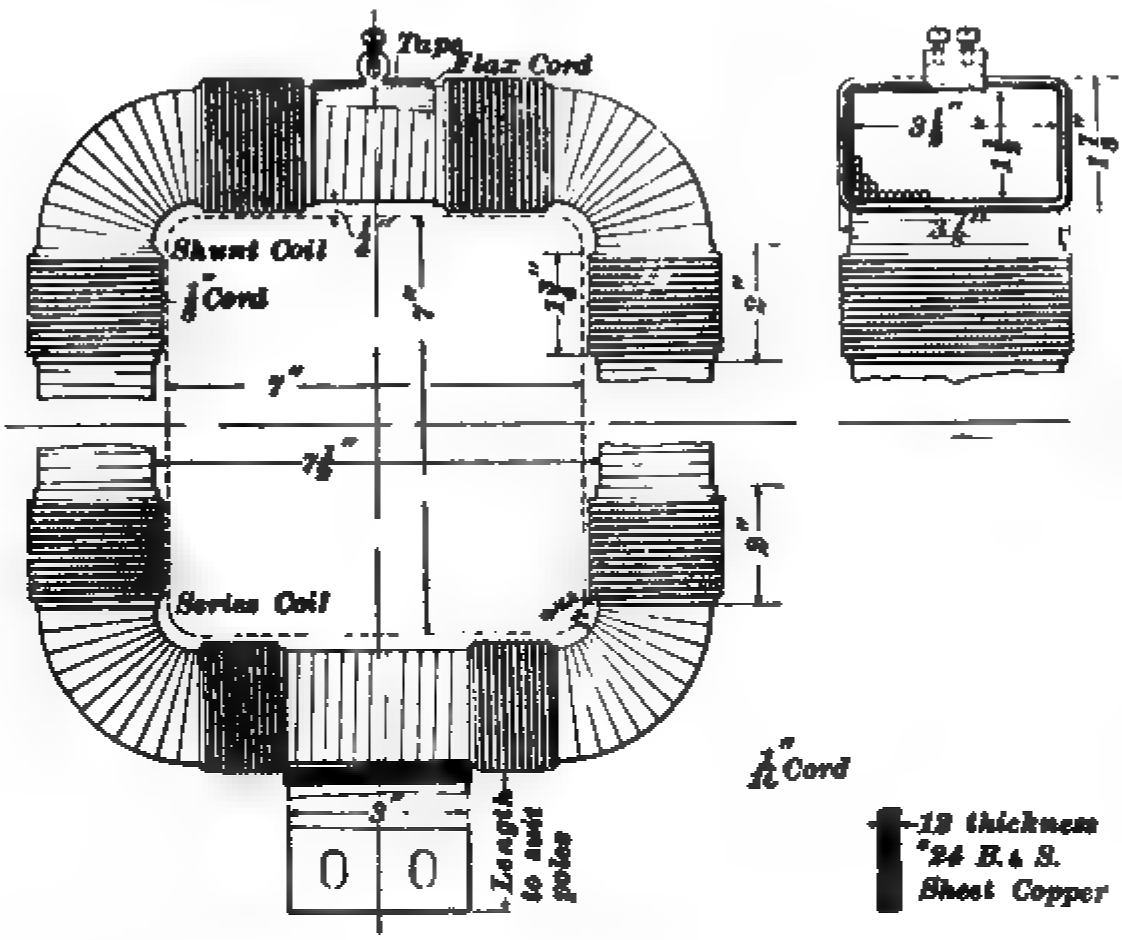


FIG. 21

and 17 layers. After the coil is wound, it is necessary to provide it with suitable terminals. If the end of the wire is left projecting for the terminal, it is liable to be broken off, and if the inner end of a coil that is wound on a spool is broken, the whole coil may have to be rewound. To avoid this, the terminals of the coils are often made of short pieces of flexible wire made of many strands of fine copper wire, which is not so easily broken. In the present case, a terminal with binding screws for attaching the leads from the

coils has been used. Such a terminal itself must be strong and firmly attached to the coil, as the wire is quite heavy, and even with the best handling, a projecting terminal is liable to receive a severe knock. The details of the coil terminal will be understood from Fig. 22. It consists of a small brass casting *a*, with a broad flat foot that sets against

Fig. 22

the coil. To the bottom of this casting is soldered a strip of copper *b*, to which in turn the end of the wire is soldered. Beneath the strip and casting is a thin sandwich *c* of press paper and oiled muslin to protect the winding and insulate it.

78. In putting on the terminals of the coils, great care must be taken to properly insulate them, as a failure of this insulation will leave the coil wholly or partially short-circuited. The voltage impressed between the terminals of a coil during its normal operation is not the only voltage it is required to withstand, for the coil surrounds a magnetic flux and any change in the amount of flux threading a coil will induce in it an E. M. F. due to its self-induction. Suppose the field circuit should be suddenly broken while there was current flowing in the coil. The flux in dying away would cause the voltage at the coil terminals to become several times as great as its normal value. This potential will be greatest at the terminals of the coil, and, referring to Fig. 22, it will be noticed that the terminal

shown connects to the under side or inner end of the coil, while the terminal itself rests on the wires of the outer layer. Between the two sides of the insulation *c*, then, there may exist a considerable voltage, and it is important, therefore, that this insulation be good and reliable.

79. After the terminals are in place they should be bound firmly to the coil with small flax cord, and then the complete coil should be insulated with a wrapping of oiled muslin, and over this a wrapping of cotton tape. The coil is next bound together at eight points with $\frac{1}{8}$-inch cord wrapped over a strip of sandwich of oiled muslin and press paper. This cord forms the chief protection for the coil, as it will be seen that the cord alone comes in contact with adjacent parts.

Formerly, it was customary to wind field coils on spools, but this practice is not greatly used today, as the spools are expensive, and the extra protection they afford is considered unnecessary, since the coils should not in their normal use be subjected to such handling as to require better protection than is given by the method just described.

80. The terminals of the series-coils consist, as shown in Fig. 21, of 12 thicknesses of sheet-copper strip 3 inches wide, and .020 inch, or No. 24 B. & S., thick. The total area of this terminal is about the equivalent of the series-coil copper, which is $\frac{1}{4}$ in. $\times$ $1\frac{1}{2}$ in. In attaching these leads to the coil proper, the copper strips should be both riveted and soldered carefully to insure a good electrical connection. Countersunk rivets should be used, and it will be necessary to place over the strips a piece of hard sheet brass $\frac{1}{16}$ in. thick $\times$ 3 in. $\times$ $1\frac{1}{2}$ in., in order to have some solid metal to hold the head of the rivet.

81. The method of connecting two series-coils that are provided with this kind of terminal will be readily understood from Fig. 23. The leads from one coil are interleaved with those from the other, and the whole clamped together, between two small brass plates, by two bolts. This joint is

excellent from an electrical point of view, for the surfaces in

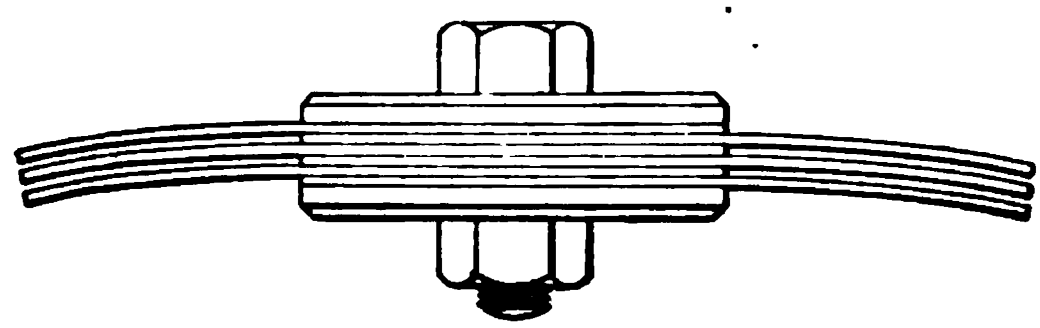


Fig. 23

contact have so great an area that the current density in the contact surface is small, as is also the resistance of the joint.

BRUSH HOLDERS AND ROCKER

82. In Fig. 24 the details of the brush holder are shown. Each of these consists of a light cast-brass pocket *a*, in

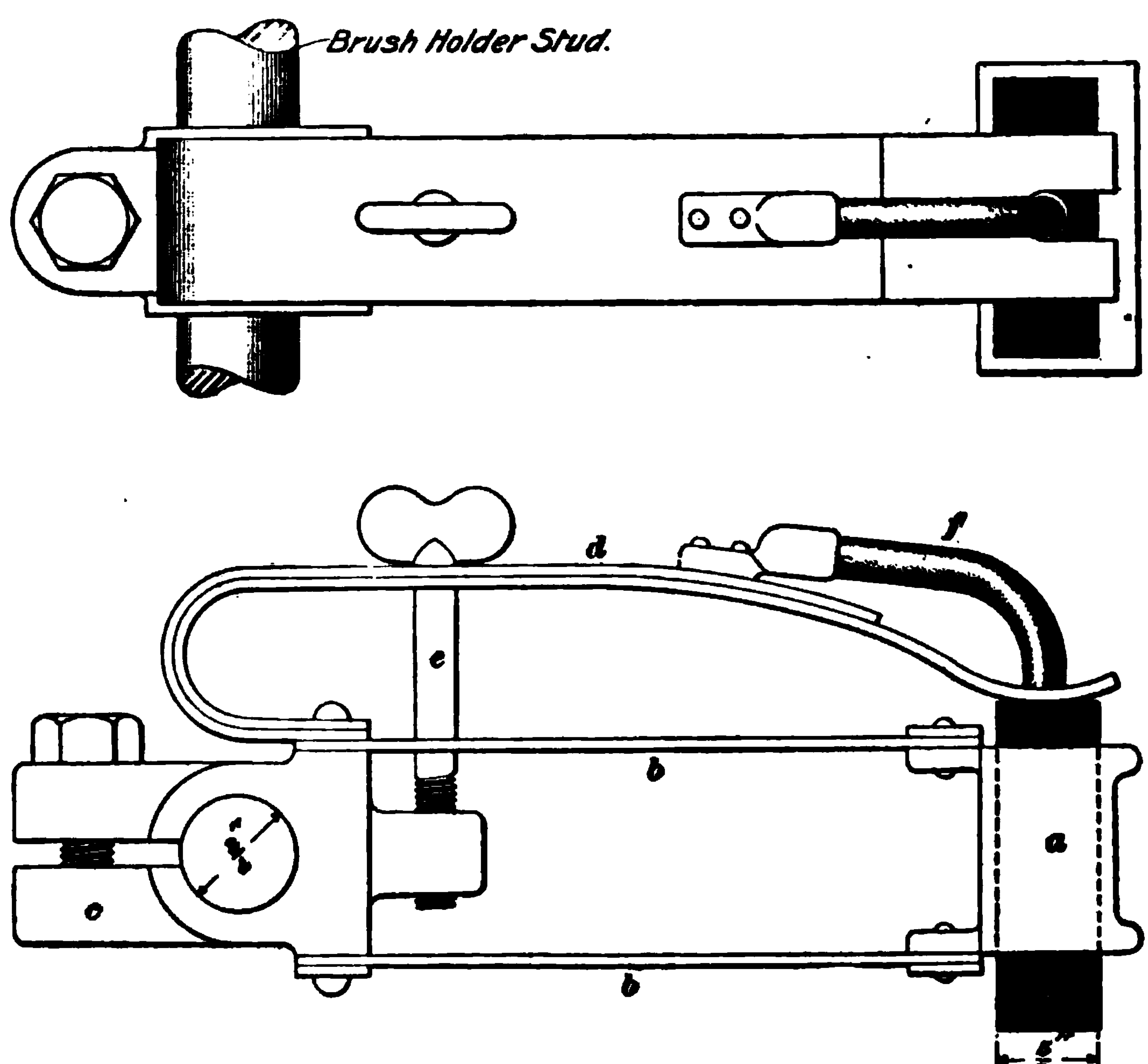


Fig. 24

which the carbon brush is capable of sliding readily. This pocket is supported by two flat springs *b*, which in turn are

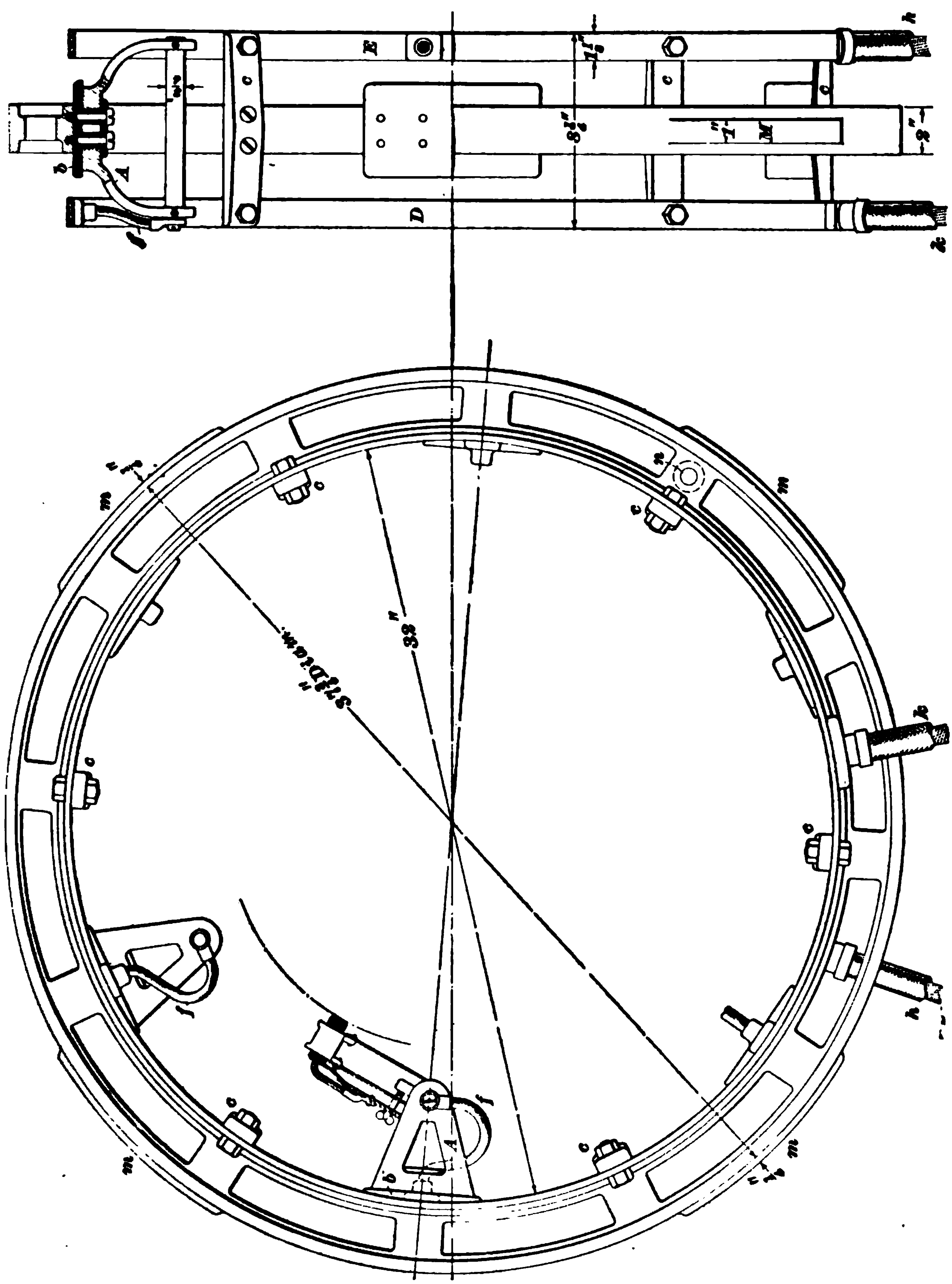


FIG. 25

attached to another casting *c* that is drilled for mounting on the brush-holder stud. To the casting *c* a flat flexible spring *d* is attached, one end of which presses against the carbon brush and keeps it in contact with the commutator. An adjusting screw *e* is provided for regulating the pressure on the brushes. It is very undesirable to have those parts of the brush holder carry current that are also used as springs, and it is especially undesirable to have to rely on the sliding contact between the brush and the metal pocket for carrying current; so, to each carbon there is attached a short flexible copper conductor, termed a pigtail, which in turn is attached to *d* at a point where there is ample cross-section for carrying the current, and therefore little likelihood of sufficient heating to draw the temper of the spring.

83. For the 250-volt generator there are four brush holders per stud. In Fig. 25 is shown the rocker-arm and the supports for the brush-holder studs. The brush-holder studs consist of a rod of brass $\frac{3}{4}$ inch in diameter, which is supported at either end by an iron casting *A*. These castings are in turn fastened to the rocker-arm or ring by four screws, but are insulated from the ring by vulcabeston washers and bushings, as shown at *b*. This construction affords a firm support for the brush holders, and insulates them thoroughly. To the rocker ring are also attached six maple cross-pieces *c*, which support at their ends two copper bus-rings *D* and *E*, one positive and one negative, to which the brush-holder studs are connected, as shown at *f*, by short flexible cables. To these bus-rings are also attached the armature leads *h* and *k*, which serve to connect the armature with the outside circuit. On the outside edge of the ring will be noticed four short lips, or ribs, *m*, that are machined to fit into groove in four arms, shown in Fig. 28, which serve to support the rocker-arm and attach it to the frame. At *n*, Fig. 25, is shown a hole drilled to receive a stud into which the adjusting screw, Fig. 28, is fastened, so that, by turning the hand wheel, the position of all brushes on the commutator can be adjusted at will. In many of the

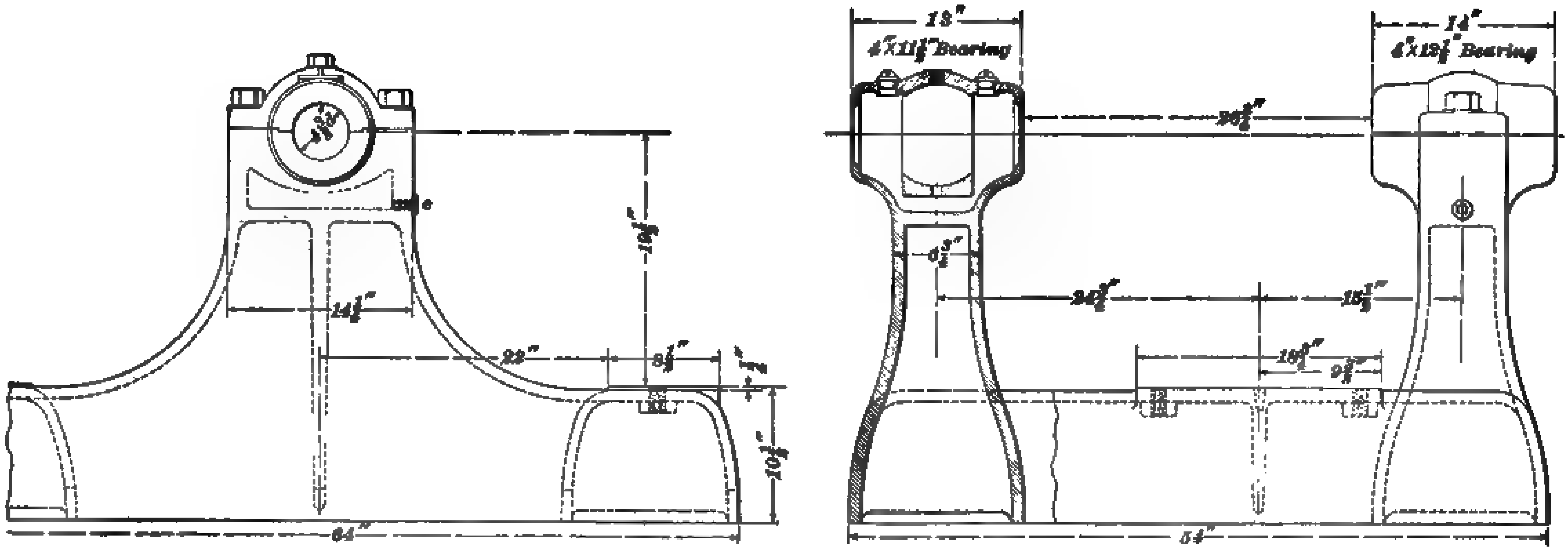


Fig. 26

earlier generators, the rocker-arm was attached to the bearing rather than to the frame of the machine. This construction has been abandoned on engine-type generators, for the reason that it is customary for the engine builder to supply the outboard bearing and pedestal, and the rocker-arm as formerly constructed would have to be specially fitted to the pedestal. The use of a ring-type rocker attached to the magnet frame is not open to this objection, the engine-type machine being complete in itself. The use of this construction for engine-type apparatus has led to its adoption on many of the belted types, as it is an advantage commercially to use the same parts for both types thus avoiding the multiplicity of parts.

BEDPLATE AND BEARINGS

84. In Fig. 26 the details of the bedplate and bearings are shown. The bedplate is cast in one piece, with the two pedestals, forming a construction that is of neat appearance and that avoids the machining of joints between the pedestals and bed. The casting, however, is complicated, and some manufacturers prefer making the bedplate separate, bolting the pedestals into place. In machines of larger size than that shown, this latter construction becomes essential, as the difficulty of machining a large casting, with pedestals cast on, outweighs the advantages of the single casting.

85. The bedplate as shown consists of a thin shell of cast iron ribbed at points to strengthen it. Such a bedplate has an appearance of solidity, and has ample strength and stiffness without requiring great weight. The pedestals are provided with caps that are bolted into place, and these hold the bearing, as shown in the section. The bearing itself is of the spherical type, so that it is capable of slight adjustment in any direction in order that the two bearings may adjust themselves properly in line. The bearing consists of cast iron, and is lined with babbitt. Oil rings *a*, *a*, that run on the shaft are provided, and grooves are cut in

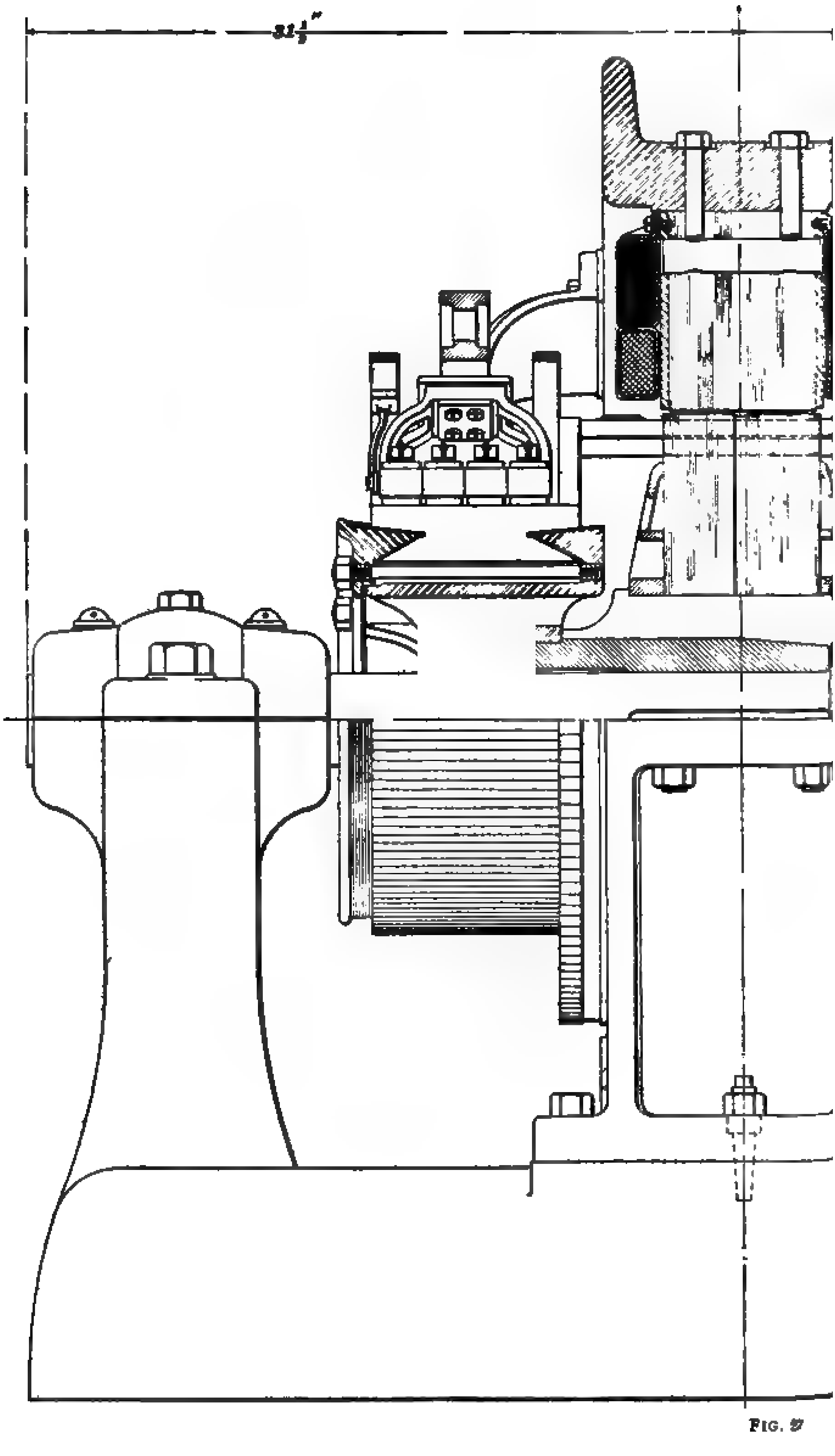
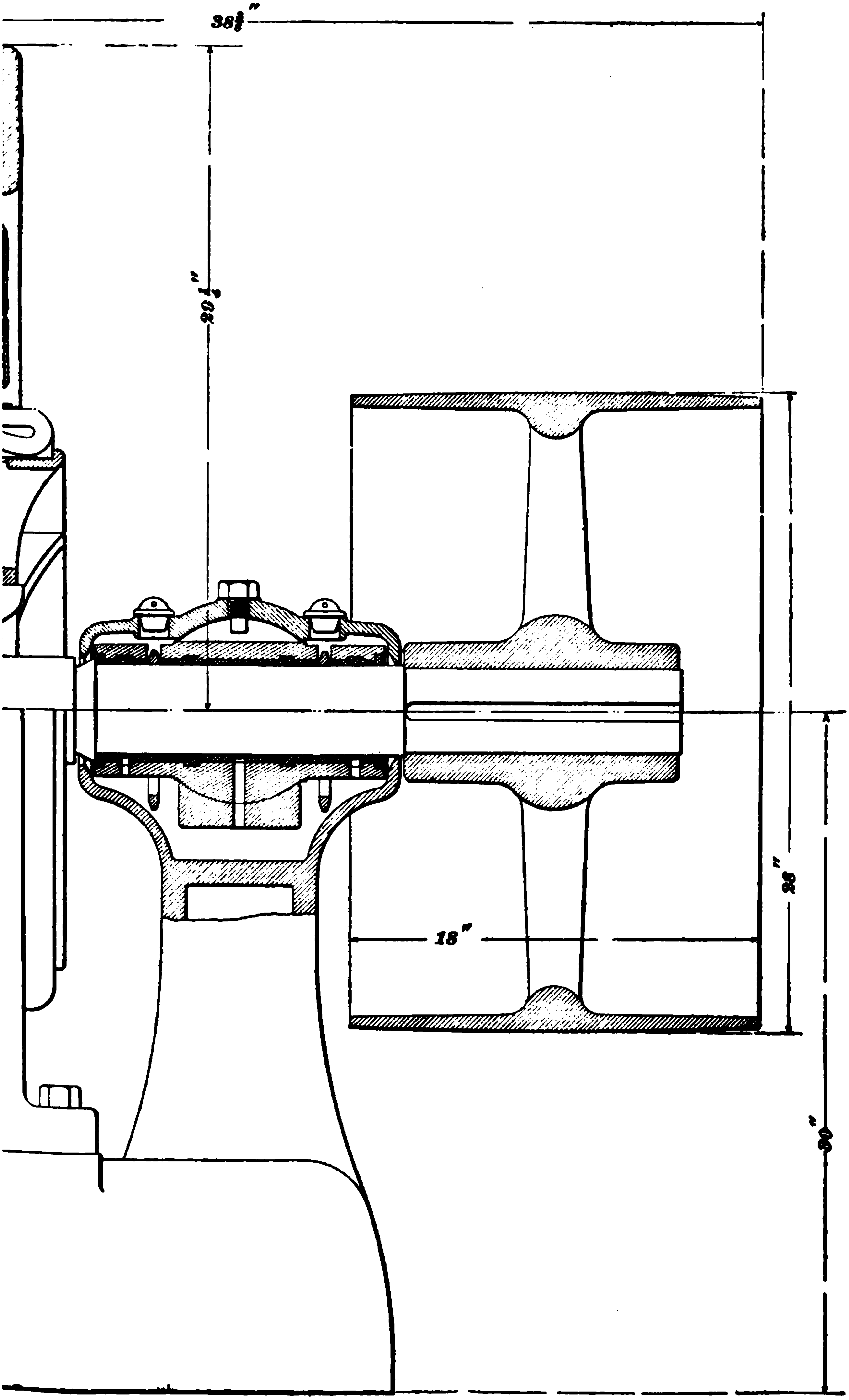


FIG. 27



38⅛"
20¼"
18"
28"
30"

the bearing shell to allow the rings to hang on the shaft and dip into lubricating oil retained in the reservoir provided in the pedestal. As the shaft revolves, the oil is carried up into the bearing by means of the rings. The oil then flows along the shaft in suitably cut grooves in the bearing, escaping back into the reservoir through the holes shown at *b*. During the operation of the machine there is a continuous flow of oil through the bearing, which not only keeps the shaft well lubricated, but tends to wash away any particles of metal that may be worn from the rubbing surfaces. In order to prevent the bearing from turning in the pedestal, a slot is cut in the former and a setscrew *c* that projects into the slot is provided in the cap. Two holes are provided in the cap, directly over the two oil rings, for the purpose of inspecting the rings to see if they are revolving freely, and also for introducing oil. These holes are supplied with two small covers *d*, as shown. The height of the oil in the oil reservoir should be such that the rings dip well into it, but should not be so high as to run out of the bearing beside the shaft. An oil gauge is attached at *e* for indicating the height of the oil in the reservoir; the gauge is shown in place in Fig. 28.

86. It is important that the oil from the bearings should not follow the shaft and run out on the armature. The oil itself is not so injurious, although it tends to destroy the insulating varnishes, but it causes an undesirable accumulation of dust that may greatly impair the insulation. It is to prevent the oil from reaching the end of the bearing that the oil grooves and the end holes *b* are provided. An oil groove is cut on the shaft, as shown at *f*, Fig. 26, so that what little oil passes out from the end of the bearing is thrown off from the sharp edge of *f* by the centrifugal force and falls within the casing.

87. Figs. 27 and 28 show the general assembly of the machine. The former shows a half section, and the relative positions of the various parts can be readily seen. The shaft is provided with two keys, one in the hub of the

armature spider and the other in the hub of a pulley. The diameter of the pulley is 28 inches, and that of the armature is 27 inches, so the belt speed will be just a little higher than the peripheral speed of the armature, which was designed for 4,000 feet per minute. This speed is about right, although it could be as high as 5,000 feet, with the advantage that the belt pull would be proportionally decreased. A low belt speed is objectionable on account of the increased pull necessary to transmit the power required. It will be noticed that the rocker-arm, with the brush holders, are shown in place, and the construction of these parts will be fully understood from Figs. 27 and 28.

Fig. 28 gives, perhaps, the best idea of the complete machine. The oil gauge is in place on the pedestal. This consists of a glass tube protected by a brass sheath, through which a slot is cut to permit the height of the oil being seen. A small cock is provided for emptying the reservoir of oil. The construction of the adjusting screw for the locker-arm will be understood from the figure. All other parts shown have been previously detailed and described.

CONNECTIONS

88. In Fig. 29 is shown a diagram of the connections of the machine. The current enters the machine from the negative lead, as indicated by arrows, and passes from the terminal board *A* directly to the negative bus-ring *B* on the rocker-arm. From this bus-ring it divides between the three brushes *C* connected thereto, going into the armature and out again at the brushes *D*, which are connected to the positive bus-ring *E*. From *E* the current passes through another flexible cable to the positive terminal board *F*, in which the leads to the series-field winding terminate; the current then passes through the series-coils and out on the positive lead. Connecting to the terminal board *F* will be noticed another outside connection, termed the **equalizer lead.** This connection is required where several compound-wound generators are operated in parallel, in order to cause

Fig.

the line current to properly divide between them. The use of the equalizer connection is fully described in the section

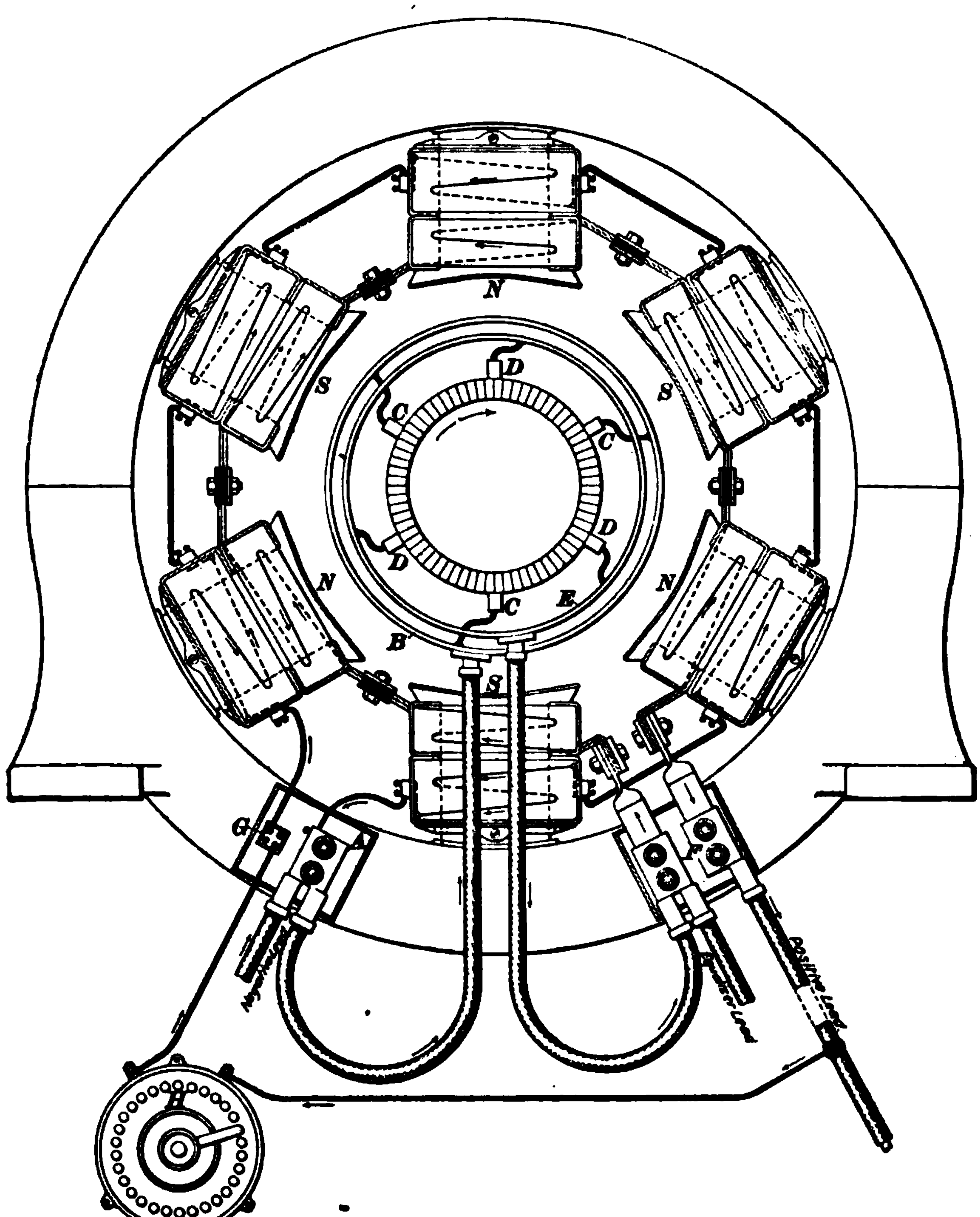


FIG. 29

relating to the operation of dynamos in parallel. When two or more machines are run in parallel, the equalizer wire connects together those brush terminals to which the series-coils are attached.

89. In Fig. 29 one end of the shunt-field circuit is connected to the armature lead on terminal board *A* and the

other end to a small terminal *G*, from which a lead wire runs to the field-regulating rheostat *H* that is connected in series with the shunt coils, the circuit being completed by a connecting wire to the positive line; this last connection is usually made on the switchboard. The direction of the currents in the coils can now be followed, and is as indicated by the arrows. It will be seen that the magnetizing effect of both the shunt coils and the series-coil on each pole is in the same direction, and inasmuch as the poles alternate *N* and *S*, it is necessary that the current in the coils on adjacent pole pieces should flow in opposite directions.

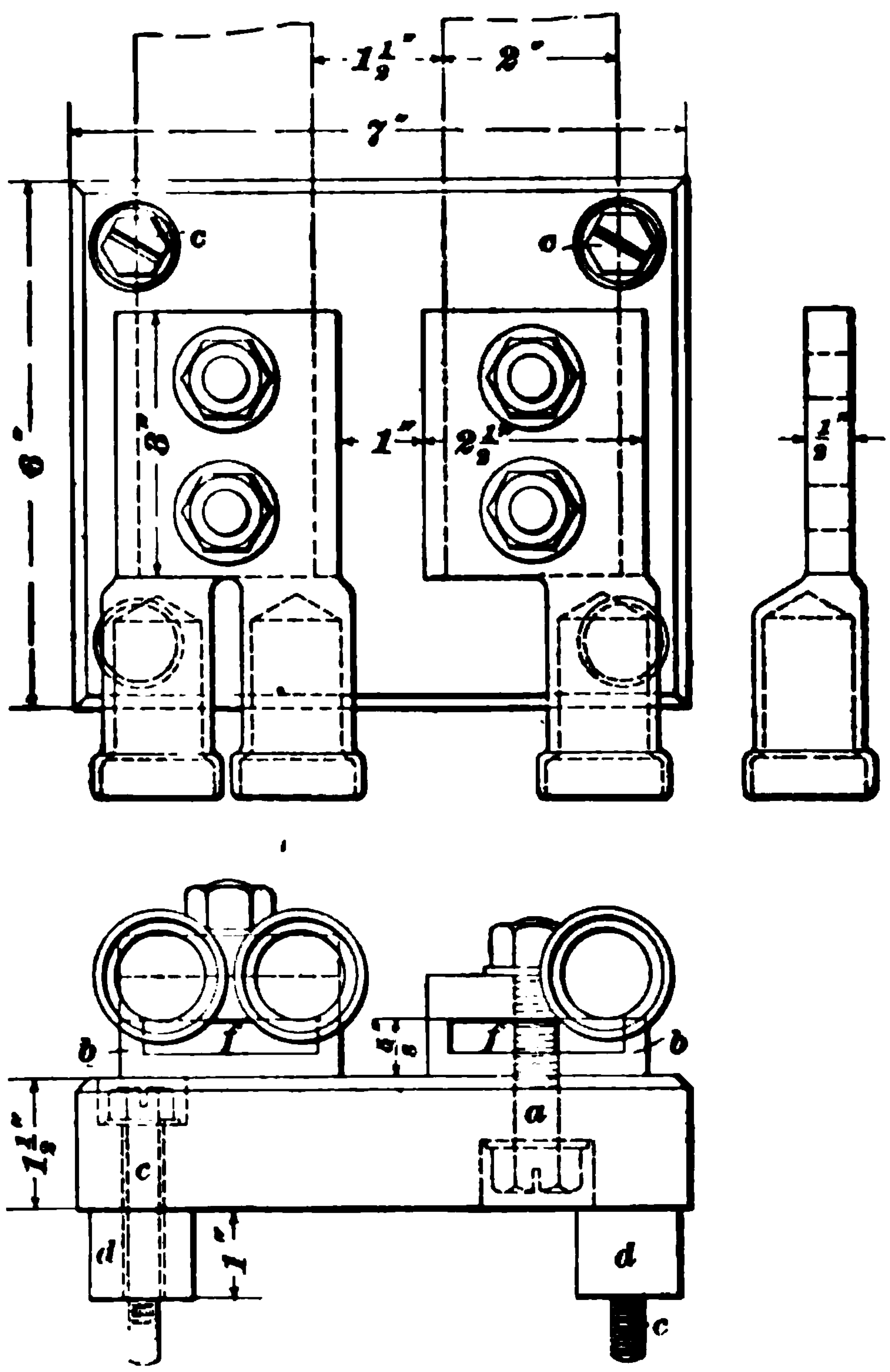


FIG. 30

90. The details of the positive and negative terminal boards are shown in Figs. 30 and 31. The flexible cables are

soldered into cast-brass terminals that are provided with flat parts of ample area, so that when bolted or clamped together, or to another connecting piece, the current density in the area in contact shall not exceed from 80 to 125 amperes per square inch. These terminals are clamped as shown by small bolts *a* that pass through the slate block and screw into

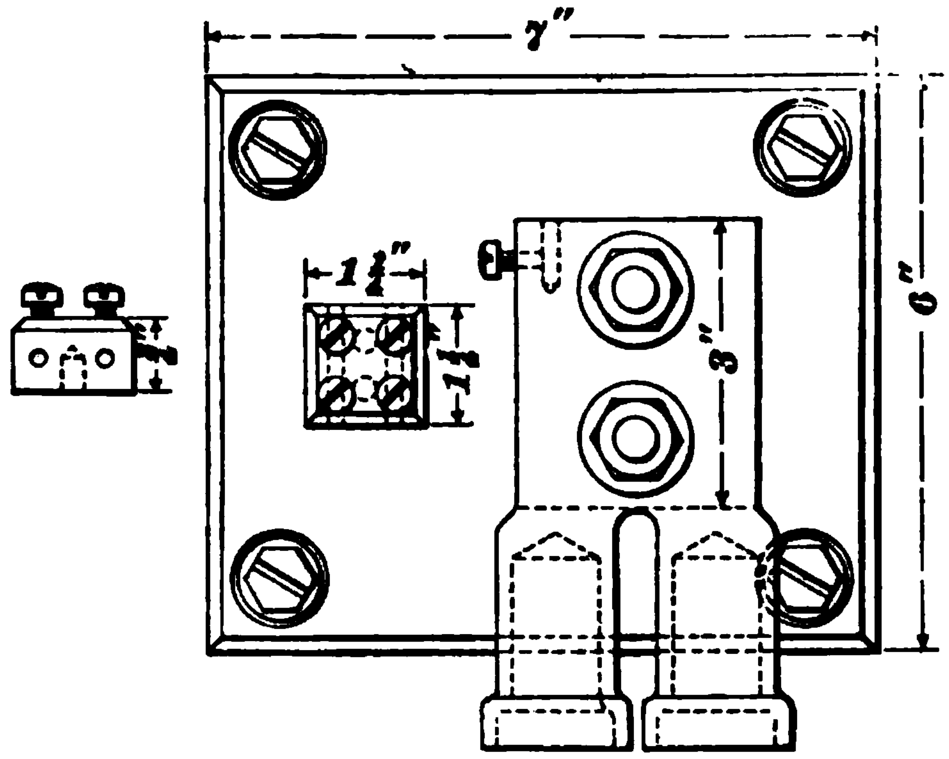


FIG. 31

small brass blocks *b*, which serve to support the terminals away from the slate. On the positive terminal board, these blocks are milled out at *f f*, to take the flat copper strip that connects to the series-coils. The slate blocks themselves are each attached to the frame of the magnet by four tap bolts *c*, and it is necessary to support the terminal blocks away from the frame by ferrules *d*, as shown, in order to insure that the screws and bolts, that attach parts carrying current and that pass through the slate, do not come into contact with the frame and thus ground or short-circuit the generator. It will be noticed that the heads of the bolts *c* that attach the terminal boards to the frame are sunk into the slate; this is done in order to prevent accidental connection between a terminal and these bolts with a wrench or other tool.

EFFICIENCY

125-VOLT GENERATOR

91. The separate losses of a dynamo may be measured or computed with considerable accuracy, and it is therefore permissible to compute the efficiency from these losses. As an example of the calculations, the efficiency of the foregoing design will be given.

The losses in a dynamo consist of two kinds, mechanical and electrical. The mechanical losses are those due to *bearing friction and windage*, *commutator brush friction*, and the *iron losses*. The electrical losses consist of the *armature I^2R loss*, the *commutator I^2R loss*, the *series-field I^2R loss*, and the *shunt-field I^2R loss*, including that in the rheostat. Consider the 125-volt machine, and let us determine the above losses in the order they are given.

92. Bearing friction and windage may, on the size given, be taken as about 1 per cent. of the output, or 1,000 watts.

93. Commutator Brush Friction.—There are required 6×6, or 36 carbons $\frac{7}{8}$ in. $\times 1\frac{3}{4}$ in., and these rub on a commutator 19 inches in diameter, which runs at 575 revolutions per minute. At this speed the friction loss may be taken as 50 watts per brush, or for 36 carbons, a total of 1,800 watts.

94. The **armature I^2R loss** can be computed from the current and the resistance. The current for 100 kilowatts at 125 volts is 800 amperes. The I^2R loss in the slots has already been computed, but for the present it is necessary to include the end connections as well as the face conductors. The area of the face conductor, .1 in. $\times \frac{5}{8}$ in., has already been determined as 76,900 circular mils, and the length of a coil may be taken as 52 inches. The resistance of a coil when warm is $R = \frac{\text{length in inches}}{\text{area in circular mils}}$, or $R = \frac{52}{76,900} = .000676$ ohm. The resistance of the armature is $R = \frac{r_c C}{m^2}$, where r_c is the resistance of a coil; C, the number of coils; and m, the number of paths or circuits through the winding. r_c in this case is .000676 ohm, C is 174, and m is 6, so that $R = \frac{.000676 \times 174}{36} = .0033$ ohm. The armature I^2R loss, then, is $(800)^2 \times .0033 = 2,112$ watts.

The resistance of the contact surfaces on the commutator is such that the drop is about 3 volts at the ordinary current

densities used in carbon brushes. At 800 amperes, this would mean a **commutator I^2R loss** of 2,400 watts.

95. Loss in Series-Field.—The series-field conductor is a copper bar $\frac{1}{2}$ in. × $1\frac{1}{2}$ in., and has been shown to have an area of 960,000 circular mils. There are $3\frac{1}{2}$ turns per coil, and 6 coils, and each turn is $34\frac{3}{4}$ inches long, so the resistance of the series-coils is $\frac{34.75 \times 3.5 \times 6}{960,000}$ = .00076 ohm. Allowing for the connections, it will be safe to call the resistance of the series-circuit .0009 ohm, so the loss in the circuit is $(800)^2 \times .0009 = 576$ watts.

96. Loss in Shunt Coils.—The current required in the shunt coils was estimated at 5.4 amperes, so the loss in this circuit, including that in the regulating rheostat, is 5.4 amperes × 125 volts, or 675 watts.

97. Summary.—The **iron losses** in the armature core have already been estimated as 2,040 watts.

The mechanical losses are as follows:

Bearing friction and windage	1,000 watts
Commutator brush friction	1,800 watts
Iron losses in armature core	2,040 watts
Total	4,840 watts

The electrical losses are:

Armature I^2R loss	2,112 watts
Commutator I^2R loss	2,400 watts
Series-field I^2R loss	576 watts
Shunt-field I^2R loss	675 watts
Total	5,763 watts

If the generator delivers 100,000 watts at its terminals, and there are 5,763 watts electrically lost, then there must have been developed 105,763 watts in the winding, and as shown in Part 1,

$$U_e = \frac{W}{W_t} = \frac{100,000}{105,763} = 94.6 \text{ per cent.}$$

which is the electrical efficiency, where W is the output and W_i is the internally developed watts.

98. The efficiency of conversion U_c has been defined as the ratio of the internal electrical watts W_i to the total watts supplied to the belt W_t. That is,

$$U_c = \frac{W_i}{W_t}$$

There are 4,840 watts lost mechanically and 5,763 electrically, so the total losses are 10,603 watts, or $W_t = 110{,}603$ watts. Hence,

$$U_c = \frac{W_i}{W_t} = \frac{105{,}763}{110{,}603} = 95.6 \text{ per cent.},$$

which is the efficiency of conversion.

The real efficiency, or the commercial efficiency, U has been defined as the product

$$U = U_c \times U_e = \frac{W}{W_t} = \frac{100{,}000}{110{,}603} = 90.4 \text{ per cent.}$$

250-VOLT AND 500-VOLT GENERATORS

99. The foregoing figures are for the 125-volt generator only, and it will be found that the 250-volt machine will have a higher efficiency, and the 500-volt machine an efficiency still higher. Let us consider how these machines differ. They all have the same bearings, bedplate, and armature core, and the bearing friction and windage will be the same on all. The magnet frame is the same, and the field windings will require about the same number of watts to set up the flux regardless of the voltage. The armature, while provided with different windings, has about the same number of circular mils per ampere and the same total ampere conductors, so that the total weight of copper and also the total I^2R loss will remain about the same for all. The commutators, however, are different for the three voltages, and the change in efficiency is due wholly to the difference in the losses in the three commutators.

100. Considering the commutator losses as computed for the 125-volt generator, the friction of 36 carbons was estimated as 1,800 watts, and the I^2R loss for 800 amperes as 2,400 watts, or the total commutator loss is 4,200 watts, which is 40 per cent. of the total losses. For 250 volts, the current is 400 amperes, and there are but 24 brushes on the commutator, so the I^2R loss in this case is 1,200 watts and the friction loss 1,200 watts, making a total of 2,400 watts for the total commutator loss. This is 1,800 watts less than for the 125-volt machine, and computing the efficiency with 1,800 watts less loss than for the 125-volt machine, we obtain a commercial efficiency of 92 per cent.

101. In the same manner, for 500 volts there are but 18 brushes, so the friction loss is about 900 watts, while the current is but 200 amperes, so the I^2R loss is 600 watts, making a total of 1,500 watts. This is 2,700 watts less than the loss for 125 volts. In this case, the commercial efficiency is 92.7 per cent.

102. It is often desired to know the efficiency of a generator at loads other than full load. A machine might have a very high efficiency at full load and yet at lighter loads have such low efficiencies as to be less economical than a machine with a high efficiency at lighter loads although having a lower efficiency at full load. The average generator in ordinary use runs at about one-half to three-fourths load most of the time, with an occasional greater load, so that the efficiency at full load is often not so important as that at lighter loads. As an example, we will compute the efficiency of the 125-volt generator at $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ load. For this purpose, it is necessary to separate the losses that change with the load from those that do not. None of the mechanical losses change with the load to any extent, while all the electrical losses, except that of the shunt field, do change.

The constant losses are:

Mechanical losses................	4,840 watts
Shunt-field loss..................	675 watts
Total constant loss..........	5,515 watts

The variable losses are:

Armature loss	2,112 watts
Commutator loss	2,400 watts
Series-field loss	576 watts
Total variable loss	5,088 watts

These variable losses depend on the square of the current, so that for one-quarter load they will be $\frac{1}{4} \times \frac{1}{4}$, or $\frac{1}{16}$ of the full load value, and at one-half load they will be $\frac{1}{4}$ of full load, and at three-quarters load $\frac{9}{16}$ of full load.

Thus:

	$\frac{1}{4}$ Load	$\frac{1}{2}$ Load	$\frac{3}{4}$ Load
Constant losses	5,515	5,515	5,515
Variable losses	318	1,272	2,862
Total losses	5,833	6,787	8,377
Output	25,000	50,000	75,000
Input	30,833	56,787	83,377
Efficiency (per cent.)	81.08	88	89.95

It is seen that the efficiency at one-quarter load is quite high, and is practically constant from one-half load to full load, being between 88 and 90 per cent.

TESTING

103. After completion, dynamos should be subjected to rigid tests to determine whether they are perfect and whether they are suitable for the service for which they are intended. The character of the tests should depend on what the machine is required to do. In order to insure getting machines of sufficient capacity, customers usually require that the machine shall be tested in a manner that they prescribe, for a certain length of time, and that its performance under test shall come up to certain desirable standards. The chief requirements are in regard to the rise in temperature, sparking, and adjustment of the brushes, efficiency, capacity to stand overloads, compounding, and the insulation of the

windings. The usual requirements in each case will be taken up separately.

104. Rise in Temperature.—It is usually required for constant-potential generators, intended for electric lighting or power, that the rise in temperature after a continuous run at full load shall not exceed 40° C., measured by thermometer on any part except the commutator, which is permitted to rise from 50° to 55° C. The temperatures are taken by thermometers placed upon the outside of the part of which the temperature is desired, and the bulb of the thermometer should be protected from drafts by a small piece of waste or other non-conductor of heat. It is further specified usually that the room temperature shall be either at 25° C., or 77° F., or referred to that temperature.

105. In the case of the windings, the change in resistance of circuits of copper conductors may be used to measure the temperature rise, for it is found that an increase in temperature of copper will increase its resistance 1 per cent. for every 2½° C. above 25°. If the rise in temperature of a coil is measured by the increase in resistance, or *by resistance*, as it is usually stated, evidently the average temperature of the interior of the coil will be obtained, and this temperature rise will always be found to be greater than that which would be obtained by a thermometer on the outside, because the latter only gives the surface temperature, while the former gives the interior temperature. Where the temperature rise is specified by resistance, it is usually required that the rise shall not exceed 50° C., or the increase in resistance shall not exceed 20 per cent. This is a more rigid requirement than 40° C. by thermometer, unless the windings are very shallow.

106. The American Institute of Electrical Engineers, in a report of the Standardization Committee, recommend specifically how these tests shall be made. A room temperature of 25° C. is recommended, and where this temperature varies, methods of correcting the results are given. The chief correction usually is for the temperature rise by

resistance, when taken in a room whose temperature changes during the test. For instance, suppose a test is begun in the morning, when it is cool, and before it is completed the room temperature should rise 10° C., or 18° F. If the resulting temperature rise by resistance should be 60° C., obviously the correct rise that is due only to the heat developed in the windings should be but 50° C.

107. Where it is specified that the temperatures shall be taken after a continuous run at full load, it is meant that the machine shall be operated until it reaches its maximum temperatures. This can be told by observing the increase in resistance of the field windings, and, when these resistances become constant, it is pretty safe to assume that the machine as a whole has reached a constant temperature, and if it is then operated 25 per cent. longer time without increase of resistances, there will be little doubt but that the ultimate temperatures for continuous operation are reached.

108. In regard to sparking, the other limit of the output of electric generators, it is usually required that machines shall operate at any load from no load to full load without change of position of the brushes and without appreciable sparking. Some customers require that machines shall operate from no load to 25 or 50 per cent. overload without injurious sparking. Generators intended for operating electric railways should be able to operate readily at 50 per cent. overload for periods of ½ hour without flashing or arcing at the brushes, and without *glowing*. Brushes in which the current density becomes too high will become red hot in spots, and this is called **glowing.** According to present practice, it is not permissible to change the adjustment of the brushes at all under variable loads; they must be set once for all and maintained in that position. The correct position for the brushes is obtained by experiment when the generator is tested, and usually the position of the rocker-arm is indicated by a mark, so that, should the machine be taken apart for shipment or repairs, the correct position of the brushes may be readily obtained when reassembled.

109. In regard to the efficiency, it has been shown that it depends on the voltage of the generator to a considerable extent. It also varies somewhat with the speed, for a machine will have a proportionately greater output at a higher speed, but the losses do not usually increase quite as rapidly as the speed; hence, the efficiency is higher for machines operating at the higher speeds. It will be well to note in this connection that, according to the American Institute of Electrical Engineers, in the case of engine-type generators, it is not customary in computing the efficiency to include bearing friction and windage. This is because the bearing friction in this case rightfully should be considered a loss of the engine rather than of the dynamo, and the difficulty of determining the losses due to air friction or windage make it necessary to omit that also. Commutator brush friction, however, should be included in the calculations.

110. Generators are required to be capable of developing greater outputs than their normal ratings for a short time without excessive heating of any part and without serious sparking, so that in case of emergency they may be relied on for overloads. For electric-lighting service, generators are usually required to stand an overload of 25 per cent. for from one to two hours, while for railway service an overload of 50 per cent. of like duration is frequently asked. Sometimes heavy overloads of long duration are demanded, but it is much better to depend on operation under full-load conditions rather than that on overloads, and this can always be done by making the capacity at full load ample for the plant under consideration.

Generators are usually required to be so wound as to develop a greater voltage on full load than on no load, but sometimes they are required to maintain the voltage constant at all loads.

In either case, the machine must be provided with a compound field winding, for where only a shunt winding is used, the terminal voltage decreases as the load is increased, because of the loss of volts in the armature and commutator

due to their resistance, and also on account of the effects of armature reactions. For electric lighting, a rise of potential of from nothing to 4 or 5 per cent. is usual, while for electric-railway and other power transmission a rise of 10 per cent. in voltage from no load to full load is customary.

111. It is usually required that the insulation of the windings of a generator should meet two requirements: (1) the insulation must have at least a specified resistance between the windings and the frame; and (2) the insulation must withstand rupture when subjected to a high voltage applied between the windings and the frame. The usual requirement for insulation resistance is that for small machines it must exceed 1,000,000 ohms, or a megohm, as it is usually stated. For large machines, it is required that the insulation resistance be such that at the normal voltage of the machine the current that will pass through the insulation must not exceed $\frac{1}{1000000}$ part of the full-load current. As an example, take a 100-kilowatt 125-volt generator. The full-load current is 800 amperes, and $\frac{1}{1000000}$ of this is .0008 ampere. Now, from Ohm's law,

$$R = \frac{E}{I} = \frac{125}{.0008} = 156{,}250 \text{ ohms}$$

The test for rupture of the insulation, or for dielectric strength, as it is termed, is usually made with voltages at least $2\frac{1}{2}$ times as great as that at which the apparatus normally operates. For small machines, for voltages under 800, from 1,000 to 1,500 volts is usually required, and for large generators, from 1,500 to 2,000 volts. The voltage is usually specified to be from an alternating-current source, as this is much more severe than a direct-current test.

112. Supposing that the requirements that a certain dynamo is expected to fulfil are known, the generator should be tested in accordance with these requirements as nearly as possible. Having provided for the disposal of the electric power developed, the machine should be brought up to speed and the cold resistances of the field circuits and the room

temperature observed and recorded. The position of the brushes for sparkless commutation should be determined by experiment, varying the current from no load to full load. The correct voltages at no load should then be obtained by adjusting the shunt-field regulating rheostat and the load applied in equal steps, to determine if the rise in voltage with the load, or the compounding, is satisfactory.

113. If the generator does not compound sufficiently, the series-coils must be rewound with a greater number of turns. If the compounding is greater than desired, it may be reduced to any amount by shunting a part of the current around the series-coils. In Fig. 32 is shown a diagram of the connections for a compound-wound generator in which the series-field coils terminate in *a* and *b*. It will be seen by the arrows that the current has two paths between these two points, one through the series-coil and the other through the resistance indicated by the zigzag line. This resistance is termed a shunt. The division of the current between these two paths depends on their relative resistances; therefore, by

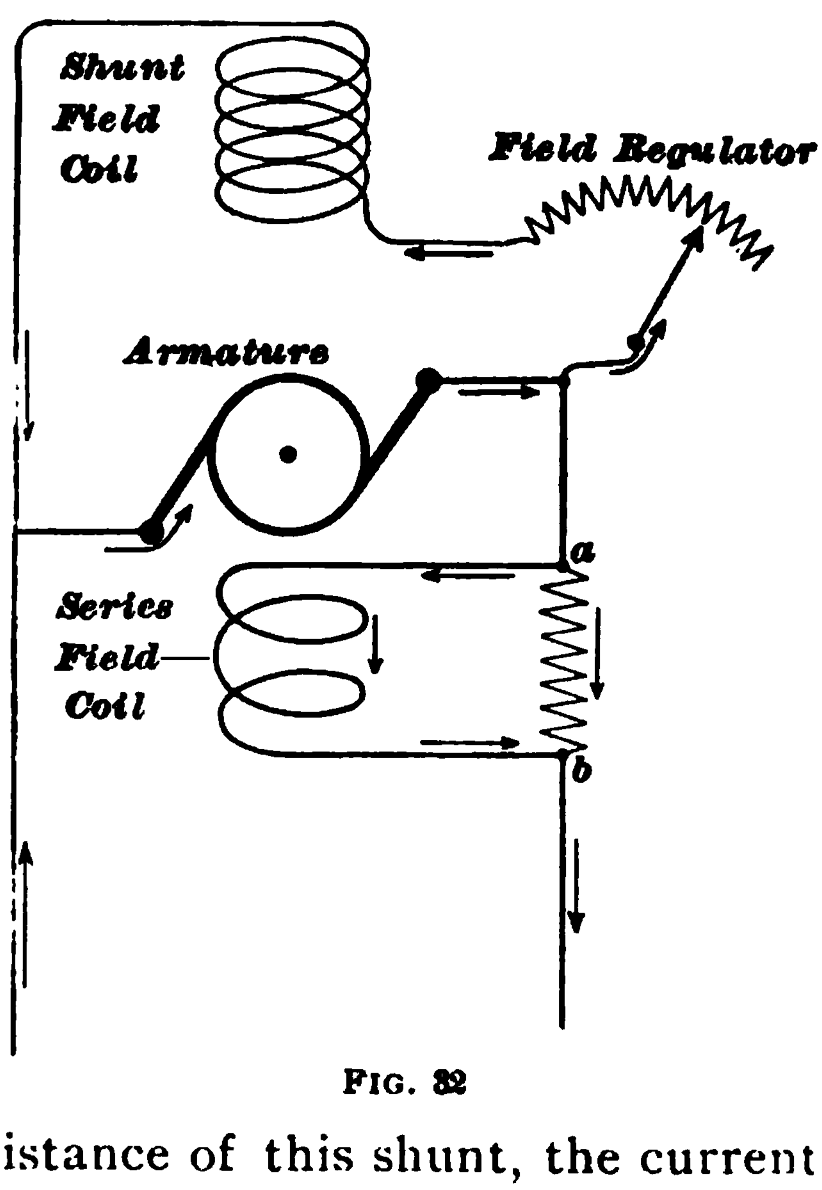


FIG. 32

properly adjusting the resistance of this shunt, the current in the series-coil, and also the series ampere-turns, can be made anything desired. Such a shunt is usually made of a German silver strip, which is folded back and forth, so as to occupy as small a space as possible. In this connection, it should be remembered that the back ampere-turns of an armature are those that lie between the double angle of lead,

and too great a lead of the brushes has the same effect as shunting a part of the current around the series-coils. Generators that do not require careful setting of the brushes to prevent sparking may sometimes be adjusted to compound properly by changing the position of the brushes.

114. When all is adjusted as desired, the test to determine the temperature rise under full load, often termed the heat test, is begun. After this is completed, the temperatures of the various parts are taken, the resistances of the field coils measured, and the compounding is again taken to determine if everything is satisfactory and within the requirements.

115. While the machine is still hot, it should be subjected to the insulation tests already described. To measure the insulation resistance, it is necessary to use a direct current, and the most convenient instrument to use is the ordinary voltmeter. The connections for this test are shown in

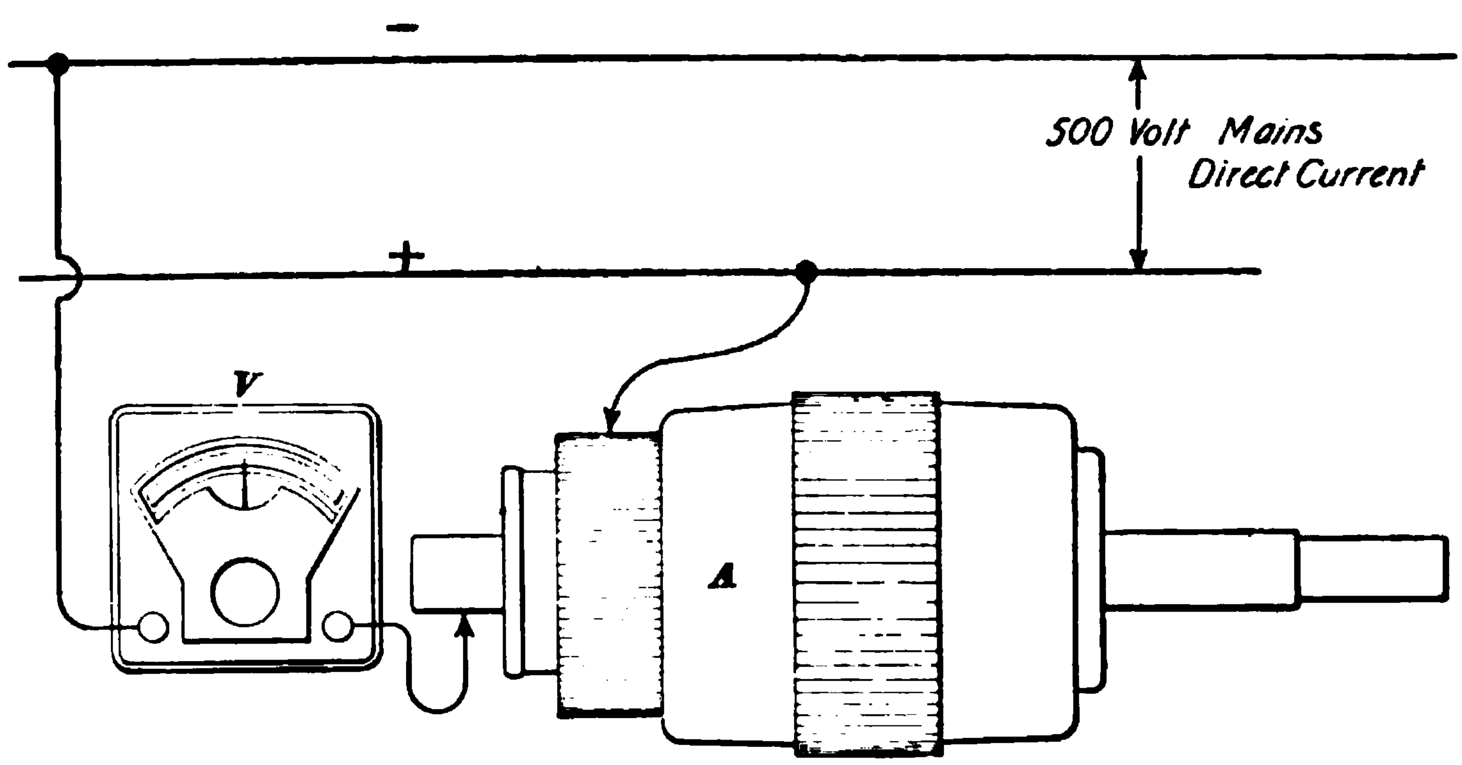


FIG. 33

Fig. 33, in which the insulation resistance of an armature is being measured by means of a 600-volt voltmeter on a 500-volt direct current. One terminal of the voltmeter connects to the line and the other to the shaft of the armature, while from the commutator a wire connects to the other side of the line. The current from the line passes to the

winding through the commutator, thence leaks through the insulation to the core, and out on the shaft to the voltmeter, and back to the line. It is clear that what current passes through the insulation also passes through the voltmeter and causes it to indicate on the scale the voltage existing at its terminals. As an illustration of the method, suppose the voltmeter used in a certain case has a resistance of 60,000 ohms, and that it indicates 10 volts when connected, as shown in Fig. 33, on a 500-volt line. If there is 10 volts difference of potential at the voltmeter terminals, there must be 490 volts between the armature winding and the core, because there are 500 volts altogether, and the current is so small that there is no appreciable drop in connections. The same current passes through the insulation as passes through the voltmeter; hence, the resistances of the voltmeter and insulation are in the same proportion as the voltages across them. The voltage across the insulation is 49 times that of the voltmeter, and the insulation resistance is $49 \times 60{,}000 = 2{,}940{,}000$ ohms, which is nearly 3 megohms. The resistance of a voltmeter is usually given with the instrument. It will be apparent, after a little thought, that a voltmeter with a very high resistance is preferable. It is also advisable that the line voltage be not less than 500 volts. An alternating current and an alternating voltmeter cannot be used for measuring the insulation resistance, since the armature will act as an electric condenser to some extent, and an alternating current can pass through a condenser, while a direct current cannot.

116. The test for dielectric strength, as has already been stated, is made with an alternating current. One terminal of the high-voltage line is connected to the windings, and the other terminal is connected to the frame of the machine. In case of defective insulation, the circuit will be completed and an excessive current will flow that may be indicated by the blowing of a fuse or other indicating device. In this case it is not necessary to measure the actual current flowing, since the test is only to show the ability of the insulation

to resist puncture. As a matter of fact, this breakdown test is by far the more important of the two, for it is possible that a weak spot in the insulation may be protected by a film of varnish and show a high insulation resistance, but a severe test on a high voltage will reveal the defect promptly.

117. The preceding tests are those to which a dynamo is subjected to determine its adaptability for certain requirements. There are, of course, very many other tests to which generators are subjected for determining certain

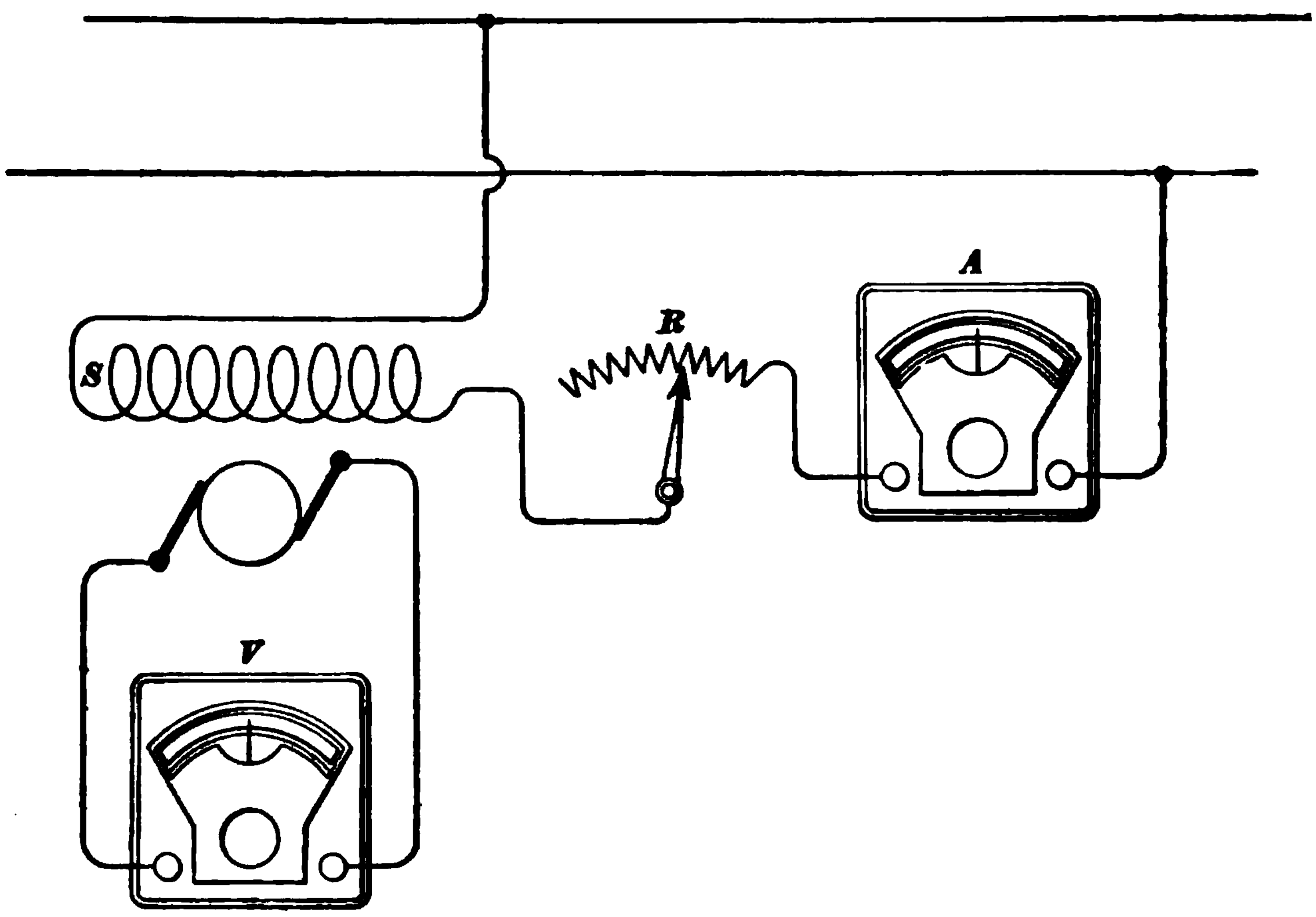


FIG. 34

particulars, but these are not, as a rule, very important in comparison to those just discussed. Among the more important tests is that from which a magnetization curve is obtained experimentally. To make this test, the connections are made according to Fig. 34. The dynamo is separately excited, so that the field current can be readily changed. In the field circuit is placed an ammeter A and adjustable resistance R, and a voltmeter V is connected across the brushes. The speed of the generator should be maintained constant, if possible, during the test, and the

brushes should be placed in the neutral position, or in such a position that the voltage obtained is the greatest under the conditions of speed and field current. The field current should now be varied by means of the rheostat R, and caused to take a series of values, the amperes in each case being read from the meter A, and the volts between the brushes read from the meter V. It is best to take the average of the readings obtained both with increasing and decreasing field currents, because on decreasing the field current, the iron of the magnetic circuit tends to retain its magnetism, and the voltages obtained are usually greater than those obtained with increasing currents. From the amperes in the field circuit, and the number of turns on the field coils, the various field ampere-turns can be computed, while the total flux per pole can be computed from the known number of armature conductors, the speed and terminal voltage. If these two values are plotted on cross-section paper, a magnetization curve like that shown in Fig. 11 will be obtained. A magnetization curve is of importance in computing the field windings. Where it is desired to rewind a machine for another voltage, it is a comparatively simple matter if a magnetization curve is obtained from the frame before the original windings are removed. The winding calculations are made after the manner already explained in connection with the design.

DIRECT-CURRENT MOTORS

PRINCIPLES OF OPERATION

DYNAMOS AND MOTORS COMPARED

1. A **dynamo** may be defined as a machine for the generation of an electromotive force and current by the motion of conductors through a magnetic field. This motion and the force necessary to maintain it must be supplied by a steam engine or other source of power. On the other hand, a **motor** may be defined as a machine for supplying mechanical power when supplied with an electric current from some outside source. The motion and the force necessary to maintain it are in this case supplied by the reaction between the current flowing in a set of conductors and the magnetic field in which the conductors are placed.

2. As far as the electrical features of a direct-current motor are concerned, they are almost identical with those of the continuous-current dynamo. The differences in the two that occur in practice are very largely differences in mechanical details that are necessary to adapt the motor to the special work that it has to do. No matter what the mechanical design of motors may be, they all consist of the same essential parts as the dynamo, namely, field magnet and armature with its commutator, brush holders, etc.

ACTION OF MOTOR

3. It is necessary to consider carefully the forces acting in a motor in order to understand clearly the behavior of different kinds of motors when operated under given conditions. In order to do this, we will consider the force acting on a conductor that is carrying a current across a magnetic field. Suppose the arrows, Fig. 1, represent magnetic lines of force flowing between the pole faces of the magnet *N*, *S*, and let *a* represent the cross-section of a wire lying at right angles to the lines. So long as no current flows through the wire, the field will not be distorted, and there will be no tendency for the wire to move. If the ends of the wire are connected to a battery so that a current flows down, this current will tend to set up lines of force around the wire, as shown by the dotted circles, Fig. 2. It will be noticed that these lines tend to oppose the original field below the wire and make it more dense above the wire. The resultant effect is that the field is distorted, as shown in Fig. 3, and the wire is forced downwards.

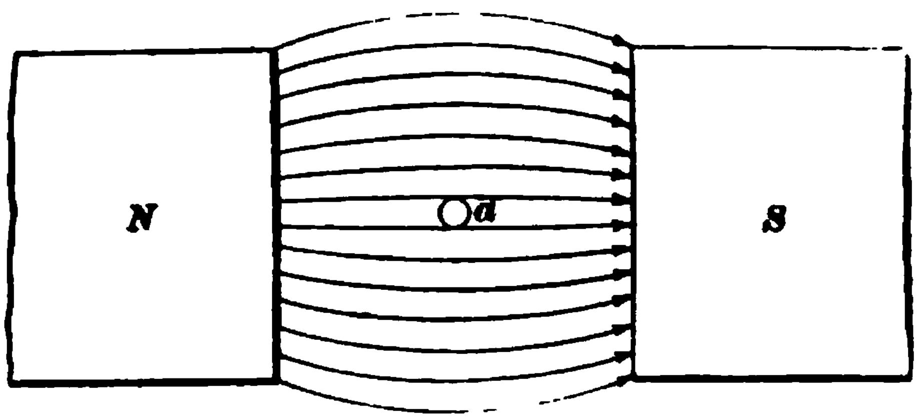


FIG. 1

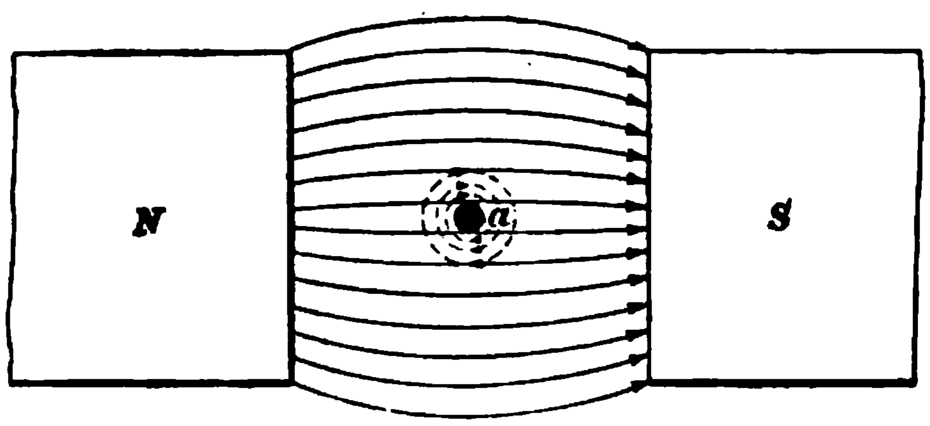


FIG. 2

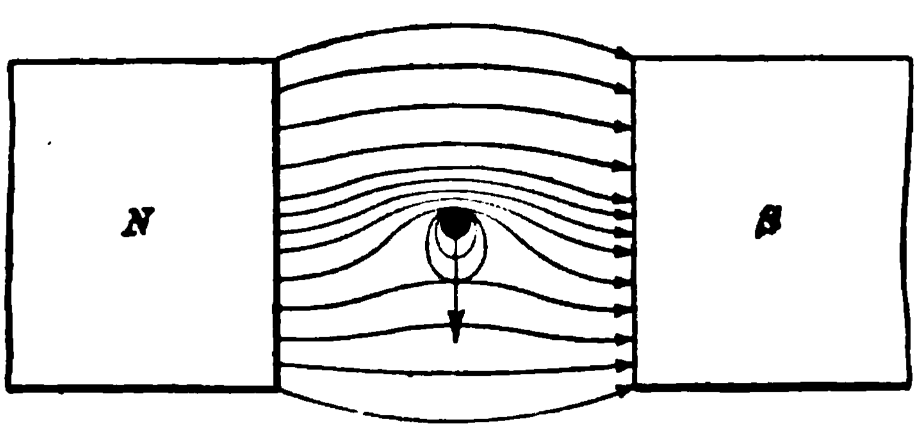


FIG. 3

4. The action described in the simple case just given is essentially that which takes place in an electric motor.

The magnet is excited by means of current taken from the mains to which the motor is connected. Current from the line is led into the armature windings by means of the commutator and brushes, and reacts on the field, thus driving the armature around

5. By referring to Fig. 3, it will be seen that in a motor the conductors are forced across the field by the reaction of the armature current on the field; that is, the force exerted by the magnetic field on the armature conductors of a motor is in the same direction as the motion of the armature. This force is made use of for doing mechanical work. The armature of a dynamo is driven by means of a steam engine or other source of power, and the armature conductors are made to cut across the magnetic field, this motion causing the generation of an E. M. F. When the outside circuit is closed, so that current flows through the armature conductors, this current reacts on the field in such a way as to *oppose* the motion of the armature. The more current the dynamo supplies, the greater is the drag between armature and field and the more work the steam engine has to do to keep the dynamo operating. In the case of a motor, the greater the load applied to the pulley, the greater must be the twisting action between the armature and field to keep up the motion, and the greater the amount of current that must be supplied from the line. It is thus seen that as regards the twisting action between the armature and field, the motor is just the opposite of the dynamo, the action in the former case being *with* the direction of motion and in the latter case *against* it.

COUNTER E. M. F. OF MOTOR

6. Whenever a conductor is moved in a magnetic field so as to cut lines of force, an E. M. F. is induced in the conductor. In the case of a dynamo this E. M. F. is made use of to set up currents in outside circuits. In other words, the E. M. F. is the *cause* of the flow of current, and consequently the E. M. F. is in the same direction as the current.

In a motor we have all the conditions necessary for the generation of an E. M. F. in the armature. It is true that the armature is not driven by a belt as in the case of a dynamo, but by the reaction between the field and armature. This, however, makes no difference so far as the generation of an E. M. F. is concerned.

When a motor is in operation, there must be an E. M. F. generated in its armature, and for the present we shall term it the **motor E. M. F.** Take the simple case shown in Fig. 3; as the conductor is forced down, it will pass across the magnetic field, and an E. M. F. will be induced in it. Also, by applying the rule for determining the direction of the induced E. M. F., we see that it must be directed upwards, that is, toward us along the conductor (the direction of motion being down and the direction of the field from left to right). The current flowing in the conductor is flowing away from us, or is being opposed by the E. M. F. We may state, then, *in an electric motor the E. M. F. generated in the armature is opposed to the current flowing through the armature.*

7. Owing to the fact that the motor E. M. F. is opposed to the current, it is commonly spoken of as the **counter E. M. F.** of the motor. It is important that the student should clearly understand the generation of this counter E. M. F. and its relation to the current.

When dynamos were first operated as motors, the existence of this counter E. M. F. was thought to be a drawback because it tended to keep the current out of the motor. It was soon found, however, that the counter E. M. F. was essential to the operation of the motor. In a dynamo we have the counter torque or drag on the armature, which the engine has to overcome; in the motor the torque assists the motion, and we have the counter E. M. F., which is opposed to the line E. M. F. Suppose a motor is connected to a constant-potential dynamo and that the armature of the motor is held from turning. There will then be no counter E. M. F. because the conductors are not cutting across the

field. The current that will flow through the armature will be fixed by Ohm's law, and will be equal to the applied E. M. F. divided by the resistance of the armature. Since the resistance of the armature is usually very low, the current will be quite large. Now, it will be noted that the motor is doing no useful work because the armature is not turning and all the energy supplied is expended in heating the armature. If the armature is released, it will at once run up to speed and at the same time the current will decrease. If a brake is put on the pulley, it will be found that as the load is increased by tightening the brake, the current through the armature increases, but it is still much smaller than when the armature was held from turning. The ohmic resistance is the same whether the armature is in motion or not, so that the large decrease in current is not due to an increase in resistance. Moreover, the dynamo supplying the current maintains a practically constant E. M. F., and the reason that the current decreases is that the moving armature introduces a counter E. M. F. into the circuit, and the E. M. F. that is effective in forcing current through the motor armature is the difference between the applied E. M. F. and the counter E. M. F.

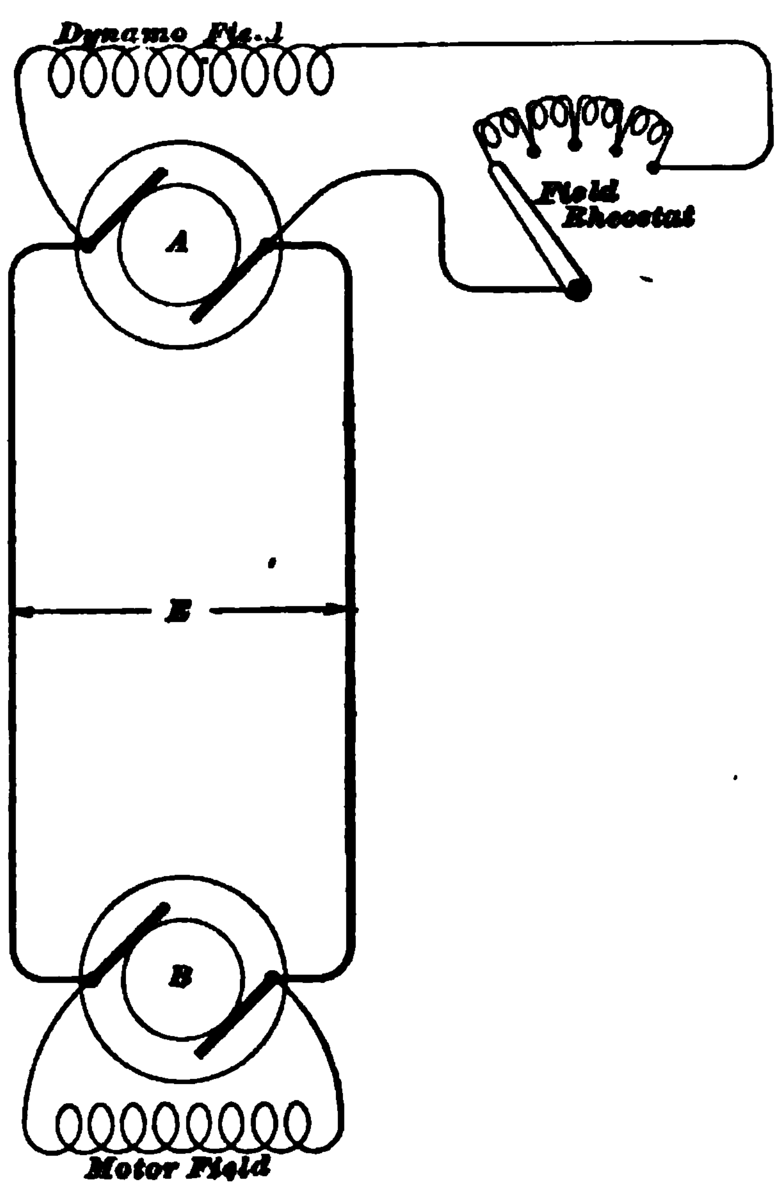


FIG. 4

Suppose the constant-potential dynamo *A*, Fig. 4, supplies current to the motor *B*. The pressure required to force a given current I through the armature is, from Ohm's law, IR_a, where R_a is the resistance of the armature. The total impressed E. M. F. E, i. e., the line E. M. F., must

be equal to the counter E. M. F. plus the E. M. F. required to overcome the armature resistance. Hence, if E_m is the counter E. M. F. of the motor, we have

$$E = E_m + I R_a \qquad (1)$$

or

$$E_m = E - I R_a \qquad (2)$$

The counter E. M. F. cannot be measured directly, but its value can be calculated if we know E, I, and R_a.

EXAMPLE.—A motor armature has a resistance of .05 ohm, and when carrying a certain load requires 200 amperes in its armature. The line pressure is 220 volts. What is the counter E. M. F. at this particular load?

SOLUTION.—The pressure taken up in overcoming the armature resistance must be $200 \times .05 = 10$ volts; hence, the counter E. M. F. must be $E_m = 220 - 10 = 210$ volts. Ans.

8. It is evident from formula **2** that if the current becomes very small (in which case the load in the motor must be very light), the counter E. M. F. E_m becomes nearly equal to the line E. M. F. E. If E and E_m were exactly equal, no current would flow through the armature. The product of E and I represents the power supplied from the line. Even if no load is applied at the pulley, some power must be supplied to keep the armature in motion; consequently, the motor must take some current whether it is loaded or not, and as current cannot flow into the motor unless the counter E. M. F. is less than the applied E. M. F., it follows that the counter E. M. F. can never be quite as large as the applied, although it may be very nearly so at light loads.

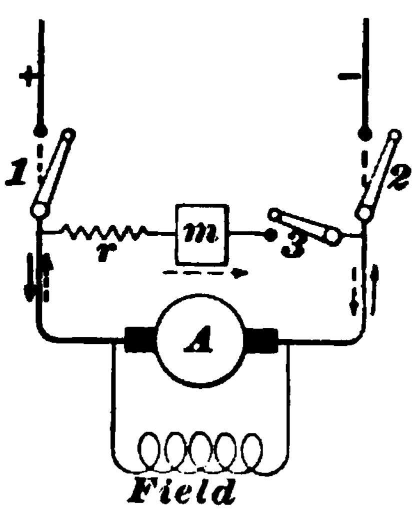


FIG. 5

The fact that a motor when running tends to set up an E. M. F. opposed to the line E. M. F. is easily shown. In Fig. 5, A is the armature of a motor, m an ammeter, r a resistance, and *1*, *2*, and *3*, switches. Suppose switches *1* and *2* are closed and switch *3* open, and that the armature is running at full speed. Then open switches *1* and *2*, and at once close switch *3*. The

ammeter *m* will show that a current is flowing, and a current will continue to flow until the energy stored in the revolving armature is used up. This generation of current by the armature soon brings it to a stop. In fact, allowing the motor to act as a generator in this way makes a very effective electric brake, and this method of braking is used quite largely for electric elevators and also, to some extent, for street cars. The ammeter will also indicate that the current flows as shown by the dotted arrows; whereas, when the motor was running from the line, the current flowed as shown by the full-line arrows. In other words, the current set up by the motor E. M. F. is opposite to that set up by the line E. M. F.

9. In a dynamo, the electrical energy developed in the armature windings is the product of the current and the E. M. F. generated in the windings. Most of this energy, but not all, is available at the terminals of the dynamo. Some of the electrical energy is lost in forcing the current through the windings. In the motor, a certain amount of electrical energy is supplied, and part of this is converted into mechanical energy within the armature. This part is represented by the product of the counter E. M. F. and the current, and it is evident that the higher the counter E. M. F. compared with the applied E. M. F., the more efficient is the motor. Action and reaction are always equal and opposite. In the dynamo, current is supplied to an outside circuit, and the reaction appears as the counter torque or the drag that the engine has to overcome. In the motor, mechanical energy is delivered at the pulley, and the reaction appears as the counter E. M. F. that the line E. M. F. has to overcome. This point is dwelt on here, because students when first studying the principle of electric motors seem to have difficulty in understanding the action of this counter E. M. F. They think it is something that prevents the proper action of the machine, whereas, it does not do so any more than the drag that the steam engine has to overcome prevents the generation of current by a dynamo.

MOTOR EFFICIENCY

10. There are certain unavoidable losses in a motor just as in a dynamo and the losses are of the same character. There are the electrical losses, consisting of the $I^2 R$ loss in the field, armature, and commutator. There are the core losses (hysteresis and eddy currents), together with the usual mechanical losses, such as friction at the bearings, brush friction, and windage. As in the dynamo, there are three efficiencies to be considered: the *commercial efficiency*, the *electrical efficiency*, and the *efficiency of conversion.*

11. Of these three the **commercial efficiency** is the most important, because it shows the percentage of the total power supplied that is converted into useful power at the pulley. The commercial efficiency takes account of all the losses in the motor. In other words, if W_t represents the total watts supplied from the lines, and W the watts available at the pulley, then

$$\text{commercial efficiency } U = \frac{W}{W_t} \qquad (3)$$

12. The **electrical efficiency** shows the relation between the amount of power developed within the armature and the total amount of electrical power supplied. The amount of power developed within the armature is equal to the counter E. M. F. multiplied by the current, and it is equal to the electrical power supplied less the various electrical losses. If W_i is the amount of power developed in the armature, then

$$\text{electrical efficiency } U_e = \frac{W_i}{W_t} \qquad (4)$$

13. All the power developed in the armature is, however, not available at the pulley. A part of it is used in overcoming the core losses and friction of the various parts. The **efficiency of conversion** is a measure of the ability of the motor to convert the electrical power in the armature

into mechanical power delivered at the pulley. The power delivered at the pulley is W; hence,

$$\text{efficiency of conversion } U_c = \frac{W}{W_t} \qquad (5)$$

14. The student should compare these efficiencies with the corresponding efficiencies for the dynamo. Since $\frac{W_i}{W_t} \times \frac{W}{W_i} = \frac{W}{W_t}$, it follows that the electrical efficiency multiplied by the efficiency of conversion gives the commercial efficiency as with the dynamo.

From the foregoing it will be seen that the points that are in favor of an efficient dynamo are also in favor of an efficient motor. The armature should be of low resistance, the shunt fields of high resistance, the core losses should be made as low as possible, and all friction should be kept within reasonable limits. In short, so far as electrical features are concerned, the machine that makes a good dynamo will also make a good motor, though its mechanical features may not be particularly adapted for some kinds of motor work.

15. The various efficiencies of a motor, as with a dynamo, vary with the load because the current varies with the load. At no load the current is very small, and all the energy taken from the mains goes to supply the losses. No useful power is delivered at the pulley, and the commercial efficiency at no load is therefore zero. As the load is increased, the commercial efficiency rises until the maximum is reached at a point depending on the design of the machine, as in the case of a dynamo. If the load on the motor is forced too high, the I^2R loss in the armature becomes excessive and the efficiency falls off.

16. Current Required by Motors.—The current that any given motor will take from the line at full load will be equal to the total number of watts supplied, divided by the line voltage. The input will be equal to the output divided

TABLE I

COMMERCIAL EFFICIENCY OF MOTORS

Output Brake Horsepower at Full Load	Commercial Efficiency
1	.650
5	.750
10	.820
12½	.850
15	.860
25	.880
50	.890
75	.900
100	.910
150	.920
200	.925

by the commercial efficiency. The full-load current, therefore, depends on the efficiency of the motor, and hence may differ by a limited amount in motors of different design. A motor might be designed to give a high efficiency at fairly light loads with a less efficiency at full load. Or it might be designed for a high efficiency at full load, with lower efficiencies at light loads. In any event the current corresponding to any brake horsepower output will be

$$I = \frac{\text{H. P.} \times 746}{E \times U} \qquad (6)$$

where I = current taken from line;
H. P. = brake horsepower (horsepower delivered at pulley);
E = line E. M. F.;
U = commercial efficiency corresponding to given load.

EXAMPLE.—A motor is capable of delivering 10 brake horsepower when fully loaded, and its full-load commercial efficiency is 85 per cent. What full-load current will this motor take from 220-volt mains?

SOLUTION.—In formula 6 we have H. P. = 10, $E = 220$, $U = .85$; hence,

$$I = \frac{10 \times 746}{220 \times .85} = 39.9 \text{ amperes} \quad \text{Ans.}$$

It will be noticed in Table I that the efficiency at first increases quite rapidly with increase in size, but as the output becomes greater, the increase in efficiency becomes smaller.

17. The current that a given motor takes at full load is usually marked on the name plate of the motor. If it is not given, the foregoing values of the commercial efficiency may be used for approximate calculations of the current. It must be understood, however, that these values of the efficiency are by no means fixed and might easily vary 2 or 3 per cent. either way from the values given.

TORQUE

18. The **torque** of a motor is the twisting or turning effort exerted on the armature. Suppose the pulley of a small motor is grasped by the hand and current sent through the armature while the field is excited. It will be found that there is a strong twisting action, or tendency for the pulley to turn, and this twisting action is known as the torque. Suppose we have a motor arranged as shown in Fig. 6. P is the pulley on which the shoes B, B press; the pressure between the shoes and the pulley can be adjusted by means of the thumbscrews N, N. To the lower block is attached an arm A provided with the point or knife edge C. This point presses on the platform scales S, so that the pressure exerted by the arm can be readily measured. The arm is balanced by the weights W, so that when the motor is standing still the arm A is just counterbalanced and there is no pressure between it and the scales. A device of this kind is known as a *Prony brake*, and by means of it the power delivered at the pulley of the motor can be measured.

Suppose for the present that the blocks B are clamped so tightly that the armature cannot turn when the normal full-load current of the motor is sent through it. Although the pulley cannot turn, there will be a strong torque, or tendency to turn, and the pin C will be pressed down against the scale platform, the scale beam registering the number of pounds pressure. It is evident that pressure obtained on the scale will depend on the length of the radius R from the center of the pulley to point C, so that it would mean nothing to state that the torque was so many pounds unless the length of the radius at which this reading was taken was

FIG. 6

also stated. For example, if the radius were made one-half as great, it is easily seen that the pressure would be doubled. In other words, torque must be expressed as a moment, i. e., by the product of a force into a lever arm. Torque is therefore expressed in *pound feet* or *foot-pounds*, the former being preferred because the foot-pound is more commonly used for the unit of work. For a given current in the armature, and given field strength, the product of force × lever arm, i. e., the torque, is a constant quantity. The number of pound feet will be the same no matter what lever arm is used, because the larger the arm, the less the force exerted

at the end of it. The number of pounds pressure on the scale will, however, depend on the length of the arm A, and the student should distinguish carefully between the force exerted in pounds, and the torque in pound feet. A motor might be giving a very small torque and yet exert many pounds belt pull, provided the pull is exerted at the end of a very short lever arm.

19. The student must also carefully distinguish between torque and power. Power is the rate at which work is done. In Fig. 6, if the brake is clamped so that the armature cannot turn when a current is sent through it, a torque will be exerted, but the motor is delivering no power because it is not running. It is possible, therefore, to have torque without power. The torque is simply the turning moment exerted on the armature, and in order that power may be delivered, the armature must be allowed to revolve.

20. Suppose, in Fig. 6, that the brake is loosened enough to allow the armature to turn but yet keep a considerable amount of friction between the shoes and the pulley. A pressure will be exerted on the scale as before, and this pressure will depend on the torque exerted by the motor. If P is the pressure in pounds on the scale, p the tangential force exerted at the pulley rim, and r the radius of the pulley, the torque is PR, which must also be equal to the force exerted at the pulley rim multiplied by the radius of the pulley; that is,

$$\text{torque} = PR = pr$$

Now, there is a steady frictional resistance of p pounds at the rim of the pulley; or we can look at it as if the motor were continuously winding up a cord to which is attached a weight of p pounds. During each revolution the weight is lifted or the resistance overcome through a distance equal to the circumference of the pulley; that is, the work done in one revolution is $2\pi r p$ foot-pounds, where the radius of the pulley r is expressed in feet. Now, if the motor is running S revolutions per minute, the number of

foot-pounds of work done per minute will be $2\pi r p S$. But the amount of work done per minute is a measure of the power developed by the motor, and $r p$ is the torque exerted, so that the power is equal to $2\pi T S$, where T is the torque in pound feet. We may, therefore, write the general relation

$$\text{power} = 2\pi \times \text{torque} \times \text{speed} \qquad (7)$$

Since the quantity 2π is constant, it follows that the power developed depends on the torque and on the speed, and while torque and power are related as shown above, they are by no means the same thing.

21. Sometimes the torque of a motor at a given current is spoken of as so many pounds. When this is done, it is always understood that this number of pounds pull is exerted at the end of a 1-foot radius, in which case the number of pounds pull is numerically equal to the torque in pound feet. It is always better, however, to express torque in pound feet so that there will be no confusion.

22. From formula **7** it is easily seen that a motor can be designed to give a certain amount of power by using different values of the torque and speed. For example, suppose a motor were to have a capacity of 10 horsepower. This capacity could be obtained by making a motor that would give a very strong torque and run at a low speed, or the same power could be obtained with a motor giving a small torque and running at a high speed. Some classes of work demand a strong torque and low speed, while in other cases a light torque and high speed are desired. The matter of torque is therefore an important one, and has to be carefully considered when motors are being designed or selected to do a given class of work.

In formula **7** the power is given in foot-pounds per minute, because the torque T is expressed in pound feet, and the speed in revolutions per minute. Since 1 horsepower is equivalent to 33,000 foot-pounds per minute, we have

$$\text{H. P.} = \frac{2 \times 3.1416 \times TS}{33,000} = .0001904\ TS \quad \textbf{(8)}$$

By making a test with the Prony brake, as shown in Fig. 6, the torque T is easily obtained, because it is equal to the scale reading multiplied by the lever arm R. The speed S can be measured with a speed counter, so that the horsepower can be at once calculated from formula **8** Formula **8** may be changed as follows:

$$S = \frac{33,000 \times \text{H. P.}}{2 \times 3.1416\ T} = \frac{\text{H. P.}}{.0001904\ T} \quad \textbf{(9)}$$

which gives the speed at which a motor must run in order to deliver a given horsepower at a given torque.

Or, $$T = \frac{33,000 \times \text{H. P.}}{2 \times 3.1416\ S} = \frac{\text{H. P.}}{.0001904\ S} \quad \textbf{(10)}$$

which gives the torque corresponding to a given horsepower and speed.

EXAMPLE.—A given motor is designed for an output of 10 horsepower, and is run on a 230-volt constant-potential circuit. When driving a certain piece of machinery it requires an electrical input of 35 amperes at 230 volts. It is desired to find the actual horsepower required to drive this machinery. The motor is disconnected from its load and a Prony brake rigged up as shown in Fig. 6. The thumb nuts are screwed up until an ammeter in the motor circuit indicates 35 amperes, the pressure across the circuit being 230 volts. Under these conditions the pressure on the scale platform is found to be 24 pounds, and the speed of the motor 800 revolutions per minute. The horizontal distance between the center of the shaft and the point pressing on the scales is 30 inches. (*a*) What is the horsepower output of the motor, and (*b*) what is the commercial efficiency of the machine?

SOLUTION.—(*a*) The distance R, Fig. 6, is 30 in. = $2\frac{1}{2}$ ft. The pressure on the scales is 24 lb.; hence, the torque = $T = 24 \times 2\frac{1}{2}$ = 60 lb. ft. $S = 800$; hence, substituting in formula **8**, we have

$$\text{H. P.} = \frac{2 \times 3.1416 \times 60 \times 800}{33,000} = 9.14 \text{ H. P., approximately} \quad \text{Ans.}$$

(*b*) The commercial efficiency is the ratio of the output to the input. The input is $35 \times 230 = 8,050$ watts. The output, since there are 746 watts in a horsepower, is $9.14 \times 746 = 6,818.4$ watts. The commercial efficiency is therefore $\frac{6,818.4}{8,050} = .847$, or 84.7 per cent. Ans.

23. Relation Between Torque and Current.—Suppose we have a motor in which the friction and core losses are negligible. The power delivered at the pulley would then be equal to the power developed in the armature. The power in watts delivered at the pulley is $\frac{2 \times 3.1416 \times T \times S \times 746}{33,000}$, where T is the torque in pound feet. If E_m is the counter E. M. F., this E. M. F. must be equal to $\frac{p\,\Phi Z S}{m \times 10^8 \times 60}$ (see *Dynamos and Dynamo Design*, Part 2). In this formula p is the number of poles, Φ the flux to or from each pole, Z the total number of armature conductors, m the number of paths in the winding, and S the speed in revolutions per minute. The power developed in the armature is equal to $E_m \times I$, where I is the current supplied to the armature. Neglecting losses, the power developed in the armature is equal to the power delivered at the pulley, or

$$\frac{2 \times 3.1416 \times T \times S \times 746}{33,000} = \frac{p\,\Phi Z S}{m \times 10^8 \times 60} \times I$$

The speed S cancels out from each side of this equation, and solving for T we have

$$T = \frac{33,000\,p\,\Phi Z I}{2 \times 3.1416 \times 746 \times m \times 10^8 \times 60}$$

$$= \frac{.00117\,p\,Z\,\Phi\,I}{m \times 10^6} \qquad \textbf{(11)}$$

Now, for any given motor the quantity $\frac{.00117\,p\,Z}{m \times 10^6}$ is fixed in value, because the number of poles p, the number of conductors Z, and the number of paths m cannot be changed. For a given motor, then, the torque T can be changed by changing the field flux Φ or the armature current I, and for a given field flux the torque depends on the current and is independent of the speed. In some kinds of motors the field flux is dependent indirectly on the speed, so that the torque varies with the speed. An examination of formula **11** shows that if a motor is to exert a strong

torque with a given current I, it must be provided with a large number of armature conductors and also have a strong field.

EXAMPLE.—A four-pole motor armature has 240 conductors arranged in a four-path winding. The flux from each pole is 2,000,000 lines. (*a*) What torque will be exerted when a current of 100 amperes is supplied to the armature? (*b*) Neglecting losses, what would be the pull at the rim of the pulley if the pulley were 20 inches in diameter?

SOLUTION.—(*a*) In this case, $p = 4$, $Z = 240$, $m = 4$, $\Phi = 2{,}000{,}000$, and $I = 100$. Applying formula **11**, we have

$$T = \frac{.00117 \times 4 \times 240 \times 2{,}000{,}000 \times 100}{4 \times 1{,}000{,}000} = 56.16 \text{ lb. ft.} \quad \text{Ans.}$$

(*b*) The radius of the pulley is $\frac{1}{2} \times \frac{20}{12} = \frac{5}{6}$ ft.; hence, the pull at the rim must be $\dfrac{56.16}{\frac{5}{6}} = 67.39$ lb. Ans.

ARMATURE REACTION

24. Armature reaction is present in motors as in dynamos, but its effects are somewhat different. Let Fig. 7

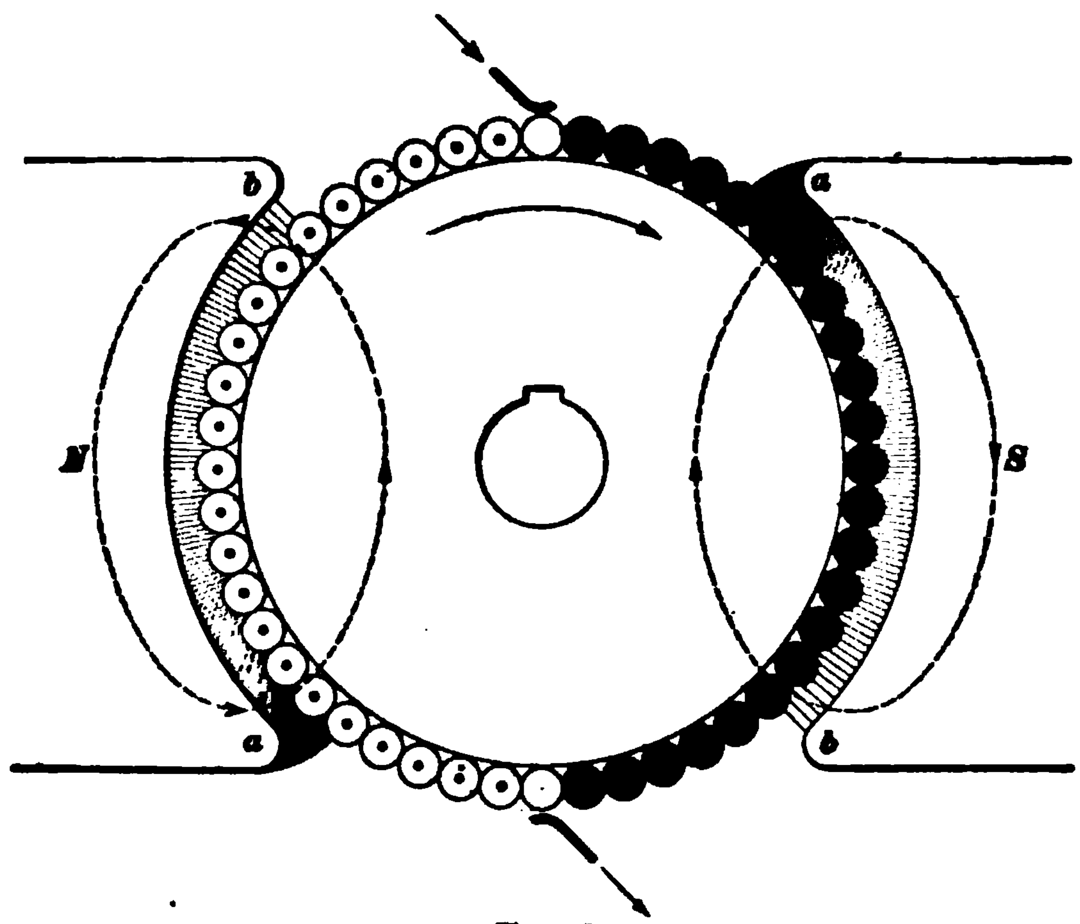


FIG. 7

represent the pole pieces and armature of a two-pole motor, and suppose current to be sent into the armature so that it flows, say, downwards in the right-hand conductors and

upwards in those on the left. Suppose for the present that the brushes are directly on the neutral line midway between the poles, as shown. The effect of the armature currents will be to cross-magnetize the field, as shown by the dotted lines, and by considering the direction of the cross-magnetism as related to the magnetism set up by the field magnet, it will be seen that the resultant effect is to weaken the pole corners *b*, *b* and to strengthen *a*, *a*. It is also evident that the direction of rotation will be as shown by the arrow, the effect of the cross-magnetization being to shift the field backwards as regards the direction of rotation instead of forwards, as in the case of a dynamo.

25. Fig. 8 shows the same armature with the brushes shifted back to the non-sparking point. The shifting of the brushes brings into play the back ampere-turns that are

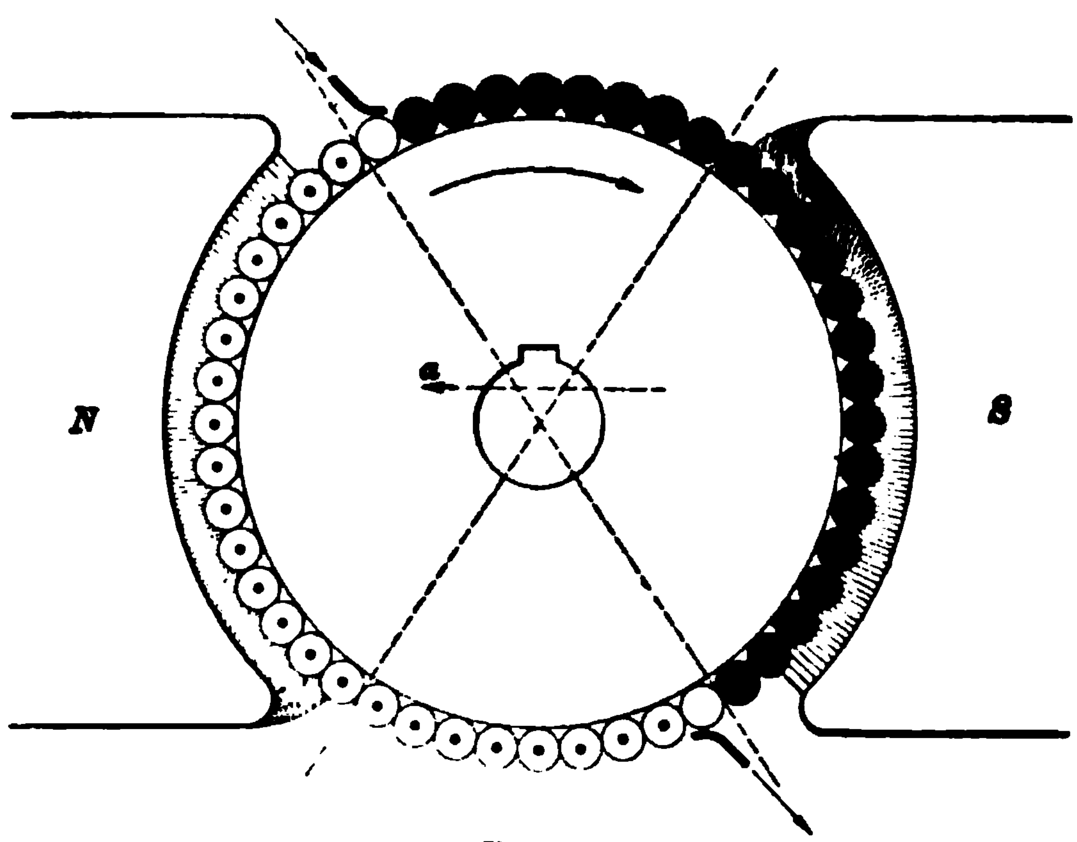


FIG. 8

included between the double angle of lead. It will also be seen that these back ampere-turns tend to *demagnetize* the field, as shown by the dotted arrow at *a*, the action of the armature in this respect being the same as the action in a dynamo. It may also be noted here that if it were possible to operate the motor without sparking, with a forward lead of the brushes, the back ampere-turns would tend to *magnetize* the field. It is important that motors be designed so

that the shifting of the sparking point from no load to full load shall be small. This means that the field should be *stiff*, or powerful, and the effects of armature reaction made as small as possible by adopting the various methods explained in connection with dynamo design. In modern motors of good design the shifting of the neutral point is very slight. Carbon brushes are used almost exclusively, and they may be left in the same position from no load to full load without sparking.

26. It is instructive to note, in connection with motor armature reaction, that if the brushes have any lead forwards or backwards and a current is sent through the armature alone, the field being unexcited, the armature will revolve, because the armature reaction will set up a field for the armature currents to react on. The torque produced would, of course, be very small, because the field set up in this way would be very weak.

CLASSES OF MOTORS

27. Direct-current motors, like dynamos, are generally classed according to the methods adopted for exciting the field magnets. This naturally divides motors into the following classes: (1) *Shunt-wound;* (2) *series-wound;* (3) *compound-wound.*

Motors may also be operated with their fields supplied from one source of current and their armatures from another. By far the larger part of the motors in use belong to the first two classes, the third class being used only to a limited extent. Nearly all motors are operated on constant-potential circuits. The voltage across the terminals is maintained constant or nearly so by the dynamo supplying the system, and the current taken by the motor varies with the load. At one time motors were operated on constant-current arc-light circuits to a limited extent. In this case the current through the motor remains constant, and the voltage across its terminals increases with the load.

SHUNT MOTORS

28. The **shunt-wound motor** is identical, so far as its electrical construction is concerned, with the shunt-wound dynamo.

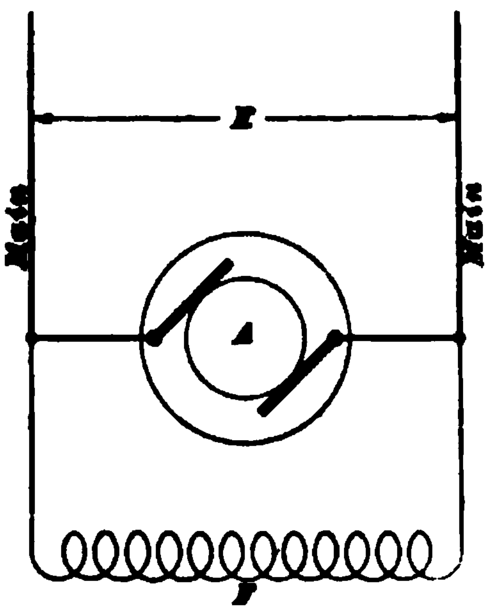


FIG. 9

These motors are operated on constant-potential systems, the motor being connected directly across the mains when running, as shown in Fig. 9, where A is the armature and F is the field. If E, the E. M. F. between the mains, is maintained constant, the current flowing through the shunt field will be constant. The field coils will therefore supply approximately the same magnetizing force, no matter what current the armature may be taking from the mains. The strength of field would be practically constant if there were no demagnetizing action of the armature.

ACTION OF SHUNT MOTOR

29. When a load is applied, the motor must take sufficient current to enable the armature to produce a torque large enough to carry the load. In order to allow this current to flow, the counter E. M. F. must lower slightly, and as the field is nearly constant, this means a slight lowering of speed. At the same time it must be remembered that the back ampere-turns will make the field flux slightly less when the motor is loaded than when it is not loaded, and this weakening of the field tends to keep the speed up. The net result, therefore, is that a shunt motor operated on a constant-potential circuit falls off slightly in speed as the load is applied, but if the motor is well designed and has a low-resistance armature, the falling off in speed from no load to full load will be very small. It is this speed-regulating feature that makes the shunt motor so widely used. If the load should be accidentally thrown off, there is no

tendency to race, and the motor automatically adjusts itself to changes in load without materially changing its speed and without the aid of any mechanical regulating devices.

Whenever the load on a shunt motor is changed, the current taken from the mains also changes, because the speed and field strength remain practically constant. Now, we have already seen that the counter E. M. F. $E_m = E - I R_a$, where E is the line E. M. F., R_a the armature resistance, and I the current. From this we have

$$I = \frac{E - E_m}{R_a} \qquad (12)$$

Now, the line E. M. F. E is constant, and the armature resistance R_a is also constant, so that if I is to increase with increase in load, it follows that E_m must decrease. Since the armature resistance is very low, a small falling off in the counter E. M. F. is sufficient to allow the increase in current needed to furnish the larger torque required to carry the added load. If the armature resistance were high, a considerable falling off in speed would accompany an increase of load.

SPEED REGULATION OF SHUNT MOTORS

30. In any direct-current motor we have the relation

$$E_m = \frac{p\,\Phi Z S}{m \times 10^8 \times 60}$$

or

$$S = \frac{m \times 10^8 \times 60 \times E_m}{p\,\Phi Z} \qquad (13)$$

It has just been shown that the counter E. M. F. E_m is nearly equal to the E. M. F. impressed on the armature. If, therefore, the E. M. F. applied to the armature is lowered while the field is maintained at normal strength, it is evident from formula **13** that S will decrease. Also, if the applied E. M. F. is increased, the speed will increase. This affords one method by which the speed of a shunt motor may be varied, namely, by varying the E. M. F. applied to the brushes.

31. In formula **13** we may keep the applied E. M. F. approximately constant and vary the speed by changing the value of Φ. The larger the value of Φ, the lower will be the speed. In other words, strengthening the field reduces the speed, because with a strong field the armature does not need to revolve as fast in order to generate the required counter E. M. F. Conversely, weakening the field, decreasing the value of Φ, causes the motor to speed up, because the armature has to revolve faster in the weak field to generate the counter E. M. F. The quantities m, p, and Z in formula **13** are fixed for a given motor so that, in general, we are restricted to the two means of varying the applied E. M. F. and varying the field strength in order to secure variations in speed.

32. Rheostatic Control.—The most common method of regulating the speed of a shunt motor is to insert an adjustable resistance R, Fig. 10, in series with the armature. This resistance cuts down the applied voltage while

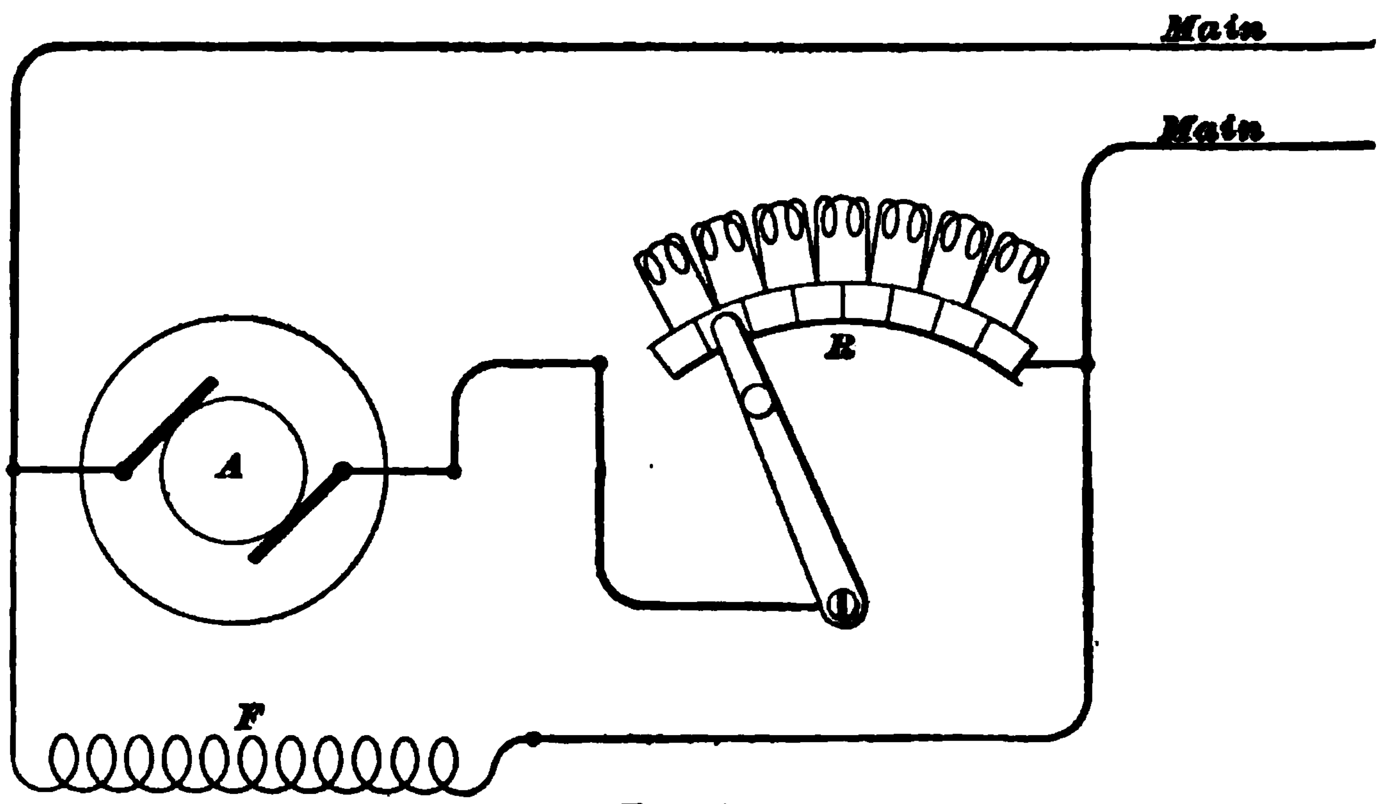


FIG. 10

the field excitation remains approximately constant. The voltage impressed on the armature is less than the line voltage by the amount of the drop in the rheostat, and it is evident that for a given position of the rheostat, this drop, and hence the speed, will depend on the load

on the motor. If the motor is running light, very little current will be required to keep it going, and the rheostat, even if it is all in, will cut down the speed but little. On the other hand, if the motor is heavily loaded, the current will be large, and a comparatively small amount of resistance in the rheostat will produce a considerable change in speed. When a rheostat is in series, therefore, every change in load will be accompanied by a change in speed, and this is a decided objection to the rheostat control for some kinds of work. Moreover, the product of the current by the volts drop in the rheostat represents so much waste power, and the rheostat method of control is not an economical one; nevertheless, it is very extensively used because it is simple and readily applied. Where a large number of motors are to be fitted for speed control, it is better to use some such arrangement as the multivoltage system described later on. Where a single motor is to be controlled, it is often cheaper to install a rheostat than a more elaborate arrangement, even if the rheostat is somewhat wasteful of power. When large motors are to be controlled, the wastefulness of the rheostatic method becomes of more concern.

33. Field Control.—If the speed control is accomplished by varying the field strength, a rheostat is inserted in the field circuit, the armature being supplied directly from the mains. This method is much more economical than where the rheostat is in the armature circuit, because with a shunt motor the field current is very small and the loss in the field rheostat is also small. Unfortunately, however, only a limited range of speed variation can be obtained by this method, because the fields cannot be strengthened very much on account of magnetic saturation, and if they are weakened below a certain limit there is sure to be sparking at the commutator. Field regulation is therefore limited to those cases where a comparatively small range of speed variation is required; usually a variation of about 25 per cent. can be obtained with an ordinary motor. Motors

designed especially for use with the field method of control may admit a range of as much as 40 to 50 per cent., but such motors must have large fields and are more expensive than ordinary motors of the same output. The subject of speed regulation will be taken up further after the other classes of motors have been considered.

SERIES MOTORS

34. These motors are constructed in the same way as series-wound dynamos. The most extensive use of **series motors** is in connection with street railways. They are also used largely for operating hoists, cranes, and other machinery of this class that requires a variable speed and strong starting effort. Nearly all series motors, like shunt motors, are operated on constant-potential circuits.

SERIES MOTOR ON CONSTANT-POTENTIAL CIRCUIT

35. Let A, Fig. 11, represent the armature of a series motor connected in series with the field F across the mains,

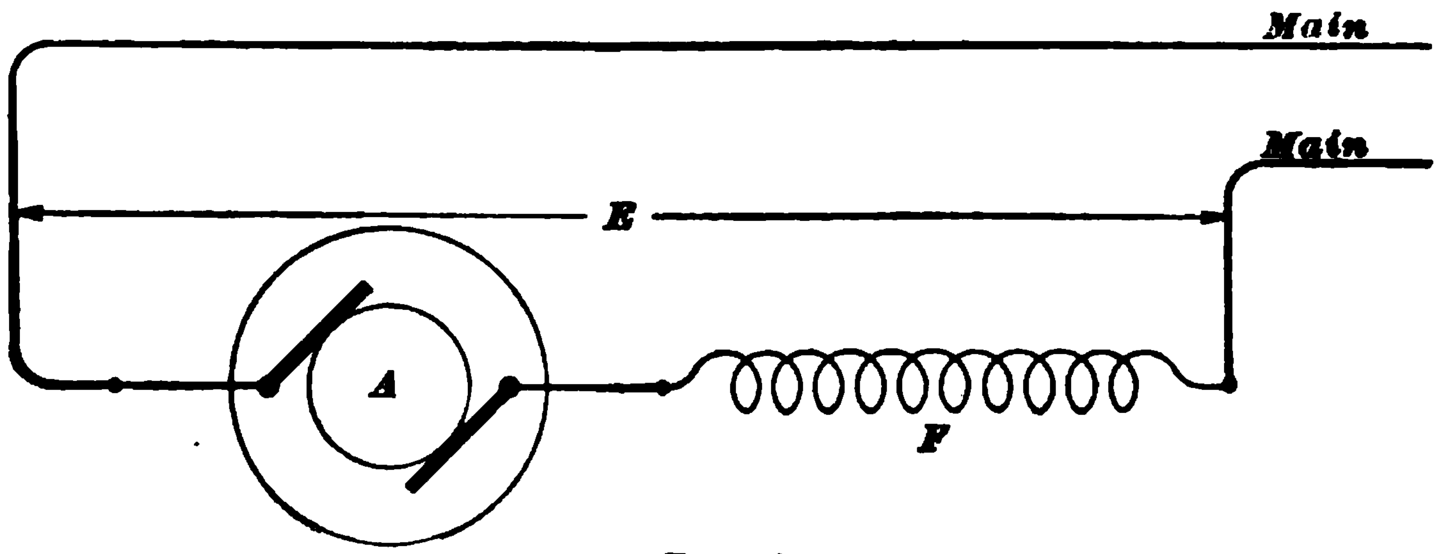


FIG. 11

as shown. The pressure between the mains is maintained constant. We will denote this constant line pressure by E. We must have, then, the following relation:

$$E = E_m + IR_a + IR_f \qquad (14)$$

where E_m is the counter E. M. F. of the motor, I the current corresponding to any given load, and R_a and R_f the resistances of the armature and field, respectively.

36. First, we will consider the case where the motor is running light. Under this condition of load, the motor will take just enough energy from the line to make up for the losses due to friction, core losses, etc. As the armature speeds up, the counter E. M. F. increases and the current rapidly decreases. Now the field is in series with the armature, so that as the current decreases, the field strength also decreases, and the armature has to run still faster to generate its counter E. M. F., which at no load is just about equal to the E. M. F. between the mains. The current necessary to supply the losses is usually very small if the motor is well designed; consequently, the no-load current is very small, and the speed necessary to generate the counter E. M F. becomes excessively high. In many cases this speed might be high enough to burst the armature. On account of this tendency to race, it is not safe to throw the load completely off a series motor unless there is some safety device for automatically cutting off the current. Of course, in street-railway work, or in the operation of cranes, hoists, etc., there is always some load on the motors, so that no injury from racing is liable to result.

37. When the motor is loaded, the counter E. M. F. decreases slightly, and this allows more current to flow. This current strengthens the field, and a correspondingly strong torque is produced. It should be noted here that the torque of a series motor depends directly on the current flowing through it. This quality renders the series motor valuable for street-railway work, as a strong starting torque can be produced by allowing a heavy current to flow through the motor while the car is being started. The series motor is capable of exerting a much more powerful starting torque than the shunt motor, because of the heavy current that flows through the field. In the case of the

shunt motor the field current is limited to the normal amount by the resistance of the coils, and, consequently, this strong magnetizing effect at starting cannot be obtained as in the series motor. Since the field strength of a series motor increases as the load is applied, it follows that the speed will decrease with the load and there will be a different speed for each load. This variable speed renders the series motor generally unsuitable for stationary work, such as operating machinery, etc., but is an advantage for street-railway work, where a wide range of speed is desired. These advantages regarding starting torque and variable speed also apply to cranes, hoists, and some kinds of rolling-mill machinery. Series motors are more substantial and slightly cheaper to build than shunt motors, on account of the fine field winding required by the latter. The field coils of series-motors consist of a comparatively small number of turns of heavy wire, making a coil that is less liable to burn-outs than the fine-wire shunt coils. In short, then, the series motor is well adapted for those classes of work requiring a large starting torque and variable speed, or where variable speed is at least not an objection.

38. Speed and Torque Curves.—The curves, Fig. 12, show the general relation between the torque and speed of a series motor. The motor is run from constant-potential mains and the load varied. At no load, the current taken by the motor is represented by Oa, and this current multiplied by the voltage represents the power necessary to overcome the frictional and core losses. Since the current is small, the magnetization is low and the speed high, the speed being represented by the ordinate Ob. With the current Oa, the torque is Oc. As the motor is loaded, the torque has to increase, and in order to supply the increased torque, the motor has to take more current from the line. As the torque and current increase, the speed falls at first very rapidly, and then more slowly as the fields become saturated, as indicated by the speed curve. It will be noticed that the torque increases in almost direct

proportion to the current, and that the speed undergoes wide variations with changes in the load.

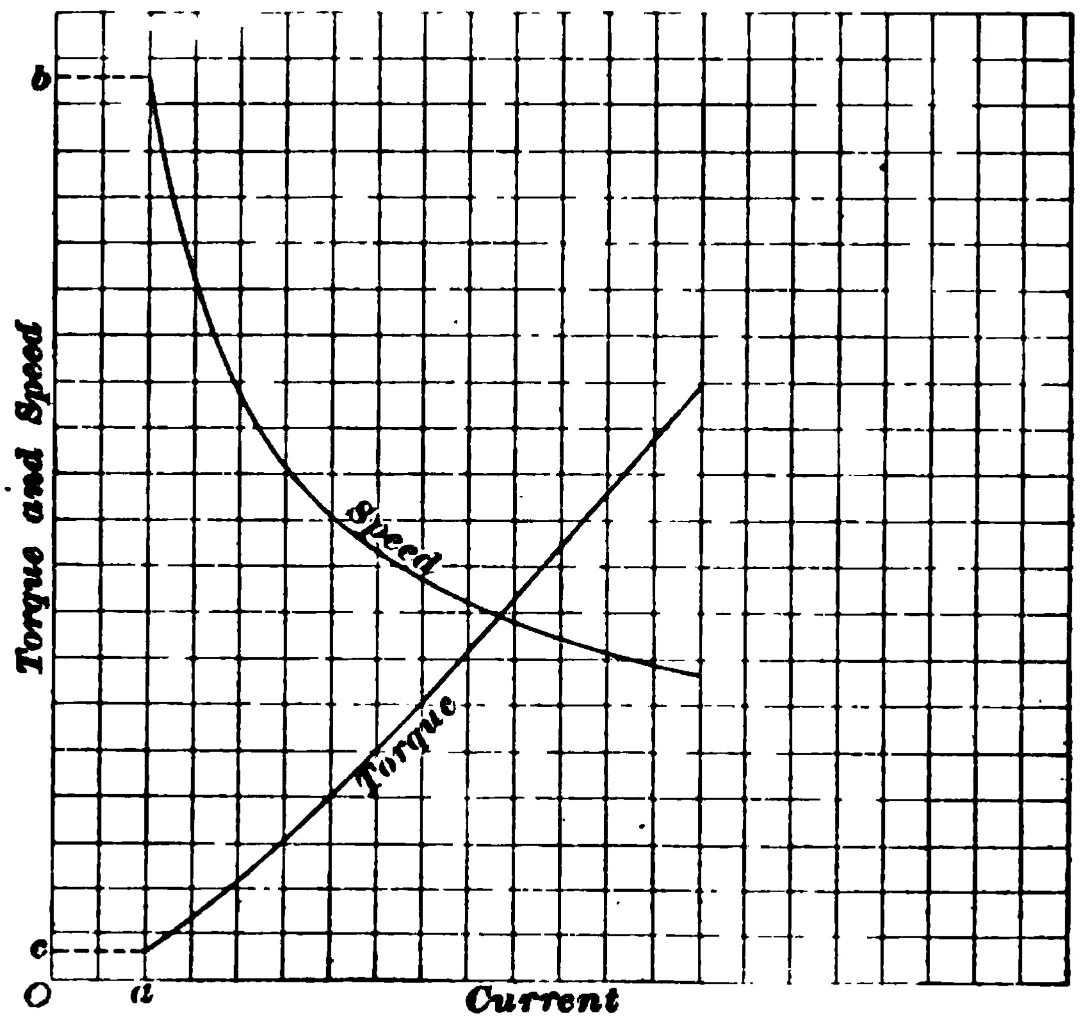


FIG. 12

39. Series Motors in Series Across Constant-Potential Mains.—Sometimes the attempt is made to operate two or more series motors in series across constant-potential mains, as indicated in Fig. 13. For example, 110-volt series-wound fan motors are sometimes connected two in series across 220 volts. Under such conditions the operation of the series motors is unstable. One of the motors

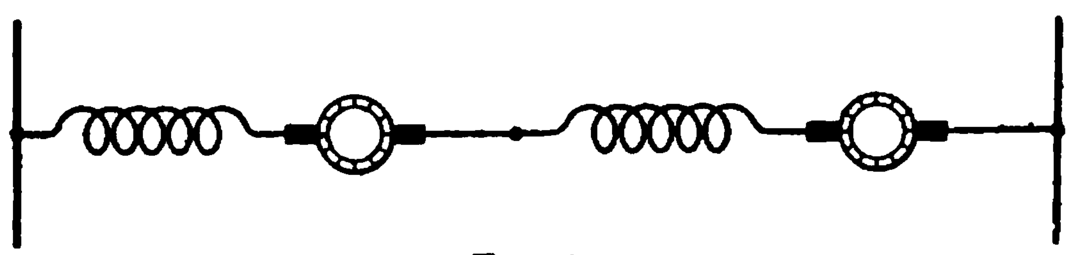


FIG. 13

may run above its usual speed, and the other run correspondingly lower, or one may even stop and the other run at a speed very much above normal. Moreover, any change in the load of either motor will cause a change in the operation of both. If the load on each motor were absolutely

equal, they would run at the same speed and each would utilize half of the power supplied from the mains. If, however, one motor is slowed up a little due to a slight increase in load, the other will speed up, thus increasing the E. M. F. across its terminals and depriving the other motor of its E. M. F. The result is that the first motor is greatly slowed down or may even stop. This unstable operation is done away with if the two motors are geared together, so that they are compelled to run at the same speed. On street cars, series motors are operated at slow speeds in series, but they are both practically geared together because they are both geared to the axles. Their operation is therefore stable unless the wheels slip on the rails. If the same motors were set up on the floor and not geared together in any way, they would show the unstable behavior referred to above.

SPEED REGULATION OF SERIES MOTORS

40. In some cases it is necessary to have the speed of a series motor under control, and this is nearly always accomplished by a rheostat in series with the motor, as shown in

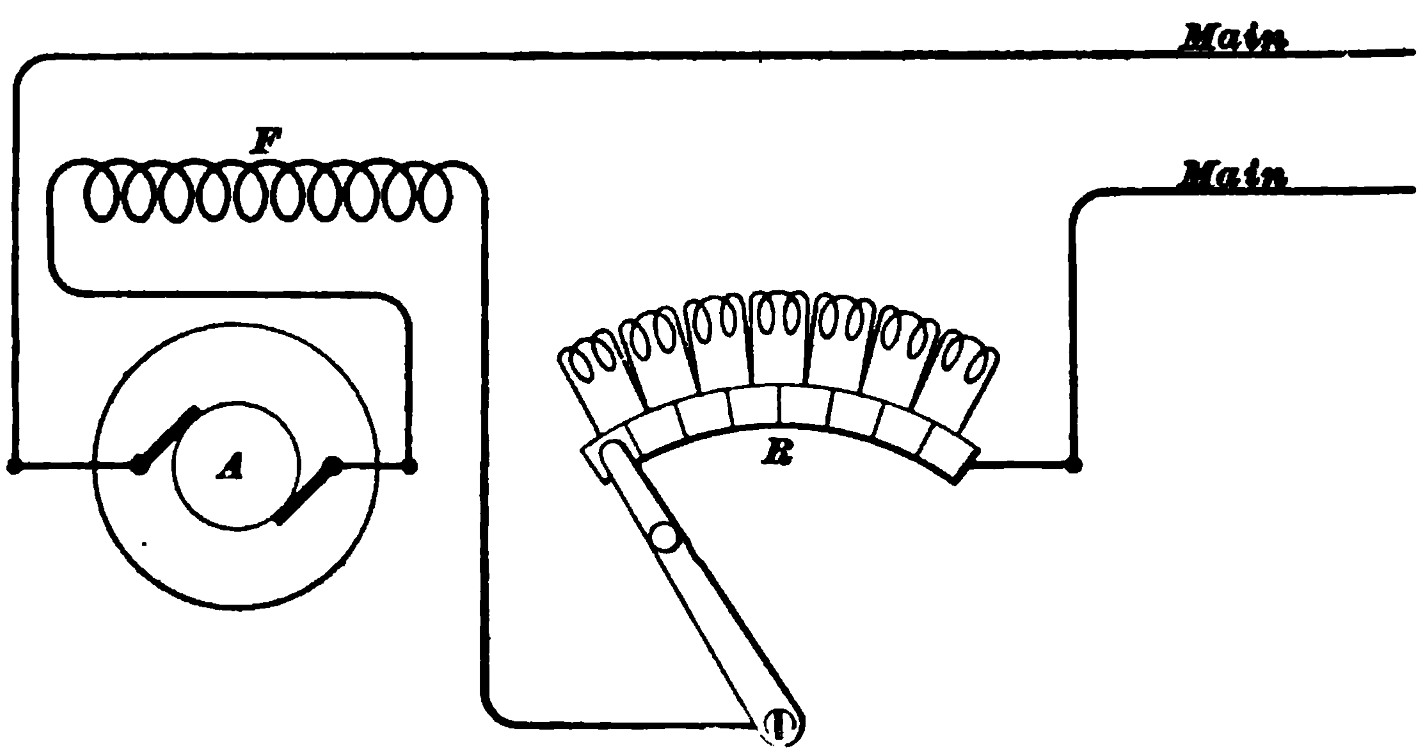


FIG. 14

Fig. 14. Sometimes the field coils are wound in sections and a switch arranged so that these sections can be cut in

or out, thus varying the speed through a limited range by changing the field strength. In other cases a variable shunt is connected across the field coils. On street cars the speed is varied by changing the voltage applied to the motors. The ordinary street car is equipped with two motors designed to operate normally on 500 volts. For low speeds these motors are connected in series across the 500 volts, thereby making the voltage applied to each motor approximately 250 volts and giving a greatly reduced speed. When a high speed is desired, the connections are changed by means of the controller so that the motors are connected in parallel across the line. This gives the full voltage across each of the motors, and allows them to run at high speed. This method of series-parallel control avoids the use of resistance for low speeds, and is therefore more economical of power than the rheostatic method; it will be described more in detail in *Electric Railways*.

41. The field magnets of series motors are sometimes provided with such a large number of turns that the field becomes fully magnetized when the current flowing is only a fraction of the full-load current of the motor. This gives a field that does not change greatly in strength for a considerable range of load, and thus tends to make the speed vary less with changes in the load, and also keeps the motor from sparking at moderate loads, on account of the strong field obtained. Street-railway motors are generally *overwound* in this way.

SERIES MOTOR ON CONSTANT-CURRENT CIRCUIT

42. It has already been mentioned that series motors have been operated to a limited extent in the past on constant-current circuits. Fig. 15 shows a series motor *M* connected in an arc-light circuit, the current in which is kept at a constant value by means of a regulator on the dynamo *D*. Since the current flowing through the field *F* of the motor is constant, the strength of field will be constant

and the torque will also be constant. If the armature were allowed to run free, it would race very badly, the racing being worse than in the case of a series motor on a constant-potential circuit, because in the latter case the current in the field and armature is reduced and the torque correspondingly cut down as the speed increases, whereas in this case the current is kept constant and the torque remains the same. It is thus seen that the speed of a series-motor operated in this way would vary widely with the load,

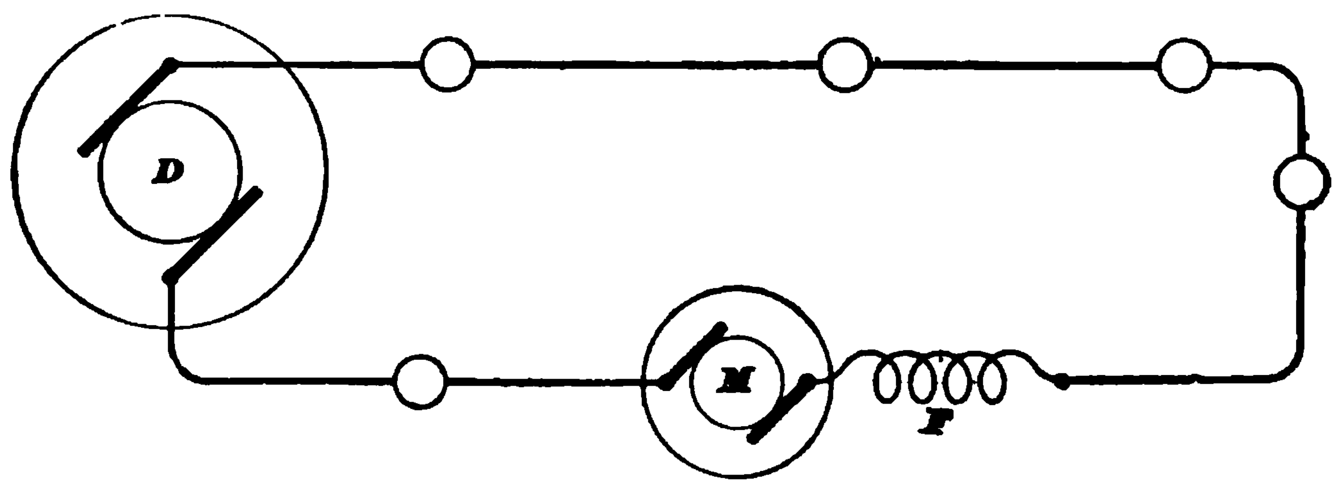


FIG. 15

and such a motor without some regulating device would be unsuitable for operating machinery. Motors are now seldom if ever operated on arc circuits. Series motors on arc circuits are always more or less dangerous on account of the high pressures generated by arc dynamos. Also, if the output of the motor is at all considerable, the pressure across its terminals at full load must be very high because the current is small.

COMPOUND-WOUND MOTORS

DIFFERENTIALLY WOUND MOTORS

43. These motors are essentially the same in construction as the compound-wound dynamo, except that the series-coils are connected so as to oppose the shunt coils instead of aid them as in the dynamo. The object of this arrangement is to secure constant speed when the

voltage of the dynamo supplying the motor is constant. These motors are not used to any great extent, because it is found that a well-designed shunt-wound motor will give sufficiently close speed regulation for all practical purposes. Fig. 16 shows the connections of a differential motor, the coils being intended to represent windings in opposite directions, one right hand, the other left hand.

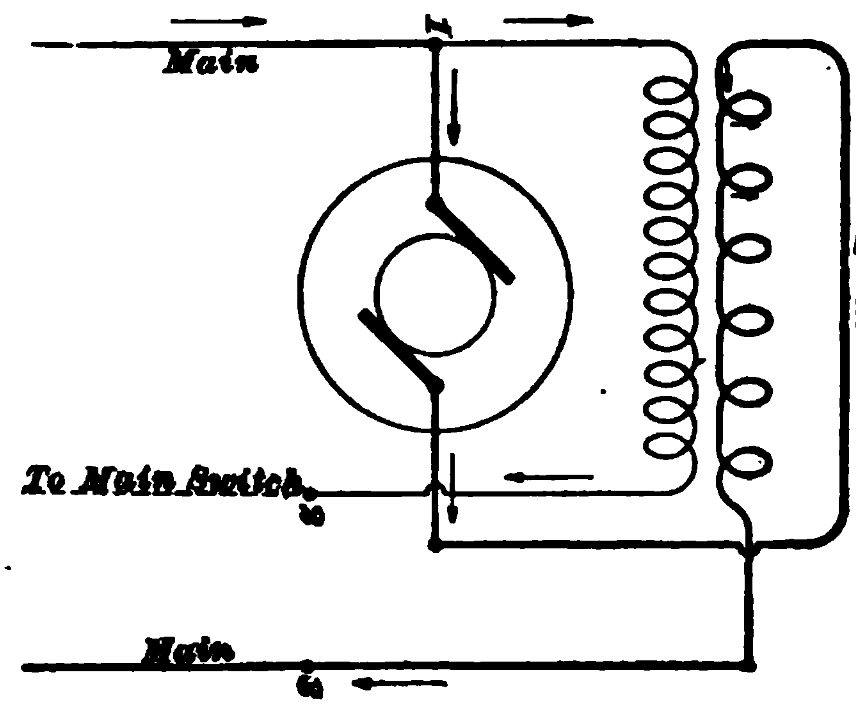


FIG. 16

ACCUMULATIVELY WOUND MOTORS

44. The **accumulatively wound motor** is the same in construction as a compound-wound dynamo. The difference between an accumulatively wound motor and a differentially wound one lies in the way in which the series-coils are used. In the accumulatively wound machine the series-coils aid the shunt coils in magnetizing the field, whereas in the differentially wound motor the reverse is the case. The accumulatively wound motor combines the features of the shunt motors and series motors. The series-coils are added in order to obtain a more powerful starting torque than that given by a plain shunt motor. These series-coils are usually cut out after the machine has been started, and the motor then runs with the shunt coils alone. The motor thus combines the strong starting torque of the series motor with the valuable constant-speed qualities of the shunt motor. Accumulatively wound motors are particularly adapted for the operation of printing presses, electric elevators, or other machinery requiring a strong starting

effort, but where the variable speed of the series motor would be objectionable. The conditions to be met in the operation of printing presses and similar machinery are particularly hard to fill, because a very strong starting effort is needed on account of the large amount of friction caused by gears, rollers, etc. After the motor has been started, a much smaller torque is sufficient. Speed control is usually obtained by inserting resistance in series with the armature for low speeds, and by cutting out the resistance for higher speeds. The series-coils are frequently wound in sections so that they can be cut out step by step, thus further raising the speed by weakening the field. Compound-wound motors are thus desirable for certain lines of work, but they are more expensive and complicated than shunt motors. For the majority of stationary machines the shunt motor is well suited, and on account of its simple construction and consequent cheapness is used much more largely than compound-wound motors, which are more in the nature of special machines.

DYNAMO AND MOTOR ROTATION

45. Very often it is desired to convert a dynamo into a motor, and the question arises as to what changes in connections are necessary. The changes required will depend on the direction in which the motor is required to run. Usually the machines so converted are shunt-wound, though sometimes they are compound-wound.

46. Shunt Dynamo Converted to Shunt Motor.—Fig. 17 (*a*) shows a machine supposed to be operating as a shunt dynamo. The armature is wound so that when the machine is driven in the direction indicated by the arrow and the polarity of the fields is as shown, the left-hand brush is positive, and the current flows out on line *1*. Consider a conductor *a* on the left-hand side of the armature, as shown in the small lower figure of (*a*). With the direction of

rotation as indicated, this conductor will be moved up across the field as shown by the vertical arrow, and the current set up in *a* will therefore be directed downwards. The wire in its motion may be looked on as bending the lines of force, and thus tending to set up right-handed magnetic whirls around itself, as indicated. Now suppose that the same machine, without any change whatever in the connections, is supplied with current from an outside source, as shown in Fig. 17 (*b*). We will also suppose that line *1* is connected to the positive main, so that the current now flows in at the right-hand brush. The current in the armature is therefore the opposite to that in (*a*), but the field remains excited

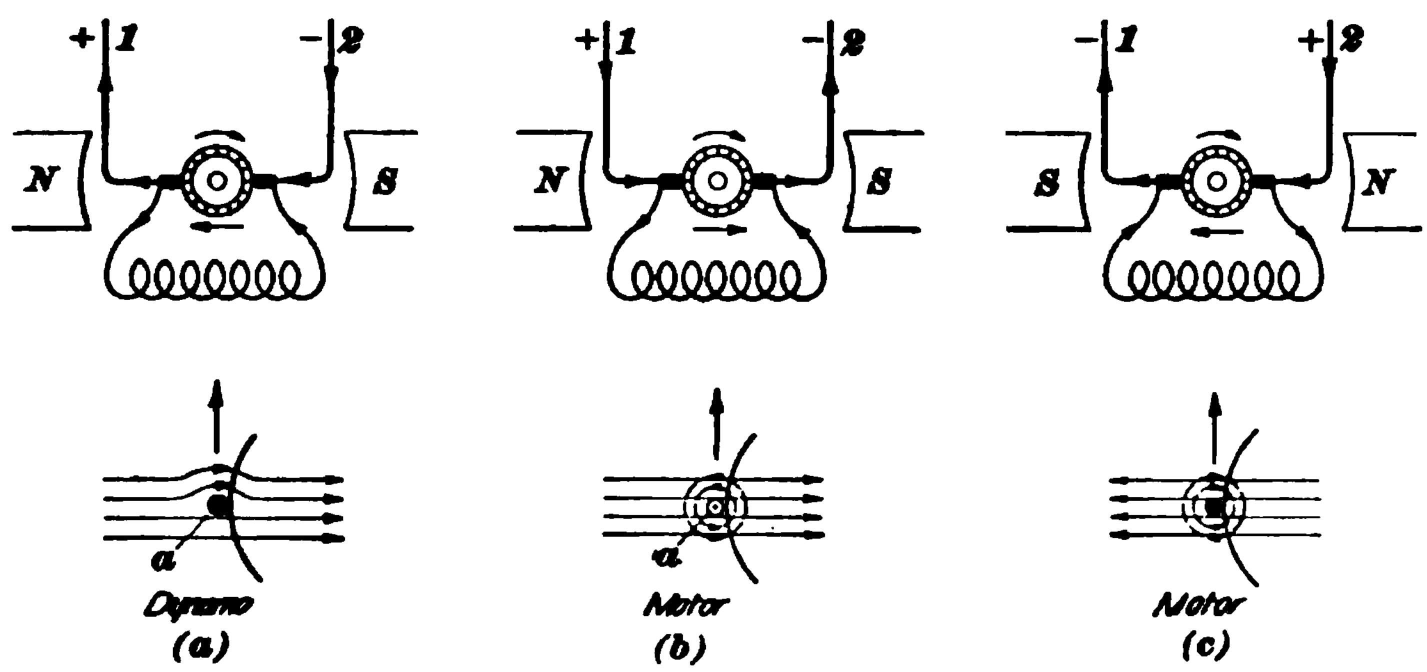


FIG. 17

in the same direction as before. The current in conductor *a* now flows up and sets up left-handed whirls, as shown by the dotted circles. These strengthen the original field below the conductor and weaken it above, thus forcing the wire up. In other words, the direction of rotation is the same as when the machine was driven as a dynamo. This property of the shunt machines is of importance when machines are run in parallel, because if one machine is *motored* by current sent back through it from another, it simply runs as a motor in the same direction in which it was driven as a dynamo and no disturbance results.

47. If the lines *1* and *2* are reversed in their connection to the positive and negative mains, as shown in Fig. 17 (*c*), the direction of rotation still remains the same because the current is reversed in both armature and field. If the motor is required to run in a direction opposite to that in which it operated as a dynamo, the field terminals should be reversed. To change a shunt dynamo to a shunt motor, then, no change in connections is necessary if the direction of rotation is to remain the same, though, of course, it is necessary to insert the necessary starting box, as described later.

48. Series Dynamo Converted to Series Motor.—Fig. 18 (*a*) shows a machine operating as a series dynamo under conditions similar to those of Fig. 17 (*a*). If this

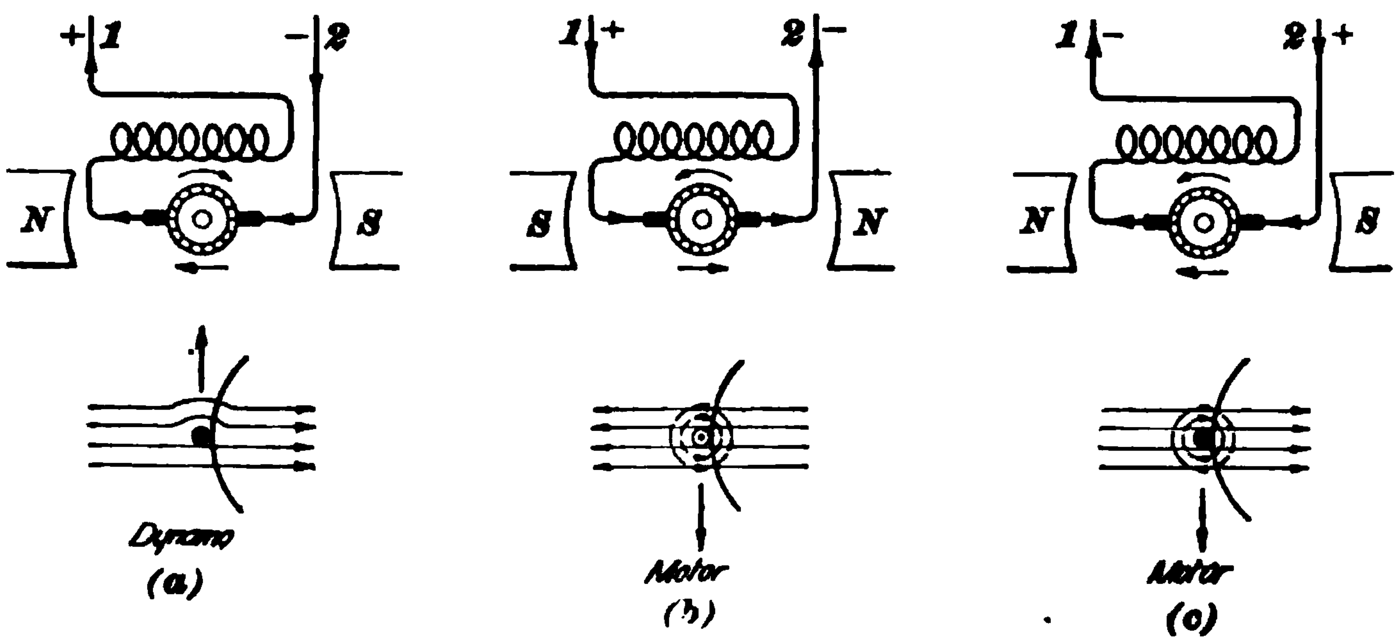


FIG. 18

machine is run as a motor having line *1* connected to the positive main, as shown in (*b*), the direction of rotation will be reversed, because the machine is now running as a motor, and the field current is also reversed in direction. The action is therefore opposite to that of the shunt motor, in which the direction of rotation remains unchanged. The direction of rotation still remains reversed if the connections to the mains are changed, as shown in Fig. 18 (*c*). If, therefore, a series machine were operating as a dynamo, and if for any reason current should flow back through it, the direction of rotation of the machine would be reversed and damage would result. If the direction of rotation as a

motor is to be kept the same as that of the dynamo, either the field or armature connections must be reversed.

49. Compound Dynamo Converted to Motor.—A compound dynamo can be converted into a motor of either the differential or accumulatively wound type. In many cases compound dynamos are converted to motors, the series-coils are cut out altogether, and the machine operated as a plain shunt motor. Since in a compound dynamo the series-coils aid the shunt, it follows that if the machine is operated as a motor without any change whatever in connections, the series-coils will oppose the shunt, and a differential motor will be obtained; if the series-coils are sufficiently powerful to overpower the shunt, the direction of rotation will be reversed. As differentially wound motors are seldom required, it will usually be necessary to reverse the series-coils connections with respect to the shunt when the machine is used as a motor, provided the series-coils are used at all.

AUXILIARY APPARATUS

STARTING RHEOSTATS

50. When motors are operated on constant-potential circuits, it is necessary to insert a resistance in series with the armature when starting the motor. Of course, in the case of a series motor, this starting resistance is also in series with the field. The resistance of a motor armature is very small, and in the case of a series motor the field resistance is also small, so that if the machine were connected directly across the circuit while standing still, there would be an enormous rush of current, because the motor is generating no counter E. M. F. Take, for example, a shunt motor of which the armature resistance is .1 ohm. If this armature were connected across a 110-volt circuit while the

motor was at a standstill, the current that would flow momentarily would be $\frac{110}{.1} = 1{,}100$ amperes, the amount being limited only by the resistance of the armature. In the case of a series motor, the rush of current would not be quite as bad, as the field winding would help to choke the current back.

51. The **starting rheostat,** or **starting box,** as it is often called, is a resistance divided up into a number of sections and connected to a switch by means of which these sections can be cut out as the motor comes up to speed. When the motor is running at full speed, this resistance is completely cut out, so that no energy is lost in it. Fig. 19 shows a simple form of motor-starting rheostat, the resistance wire in this particular type being bedded in enamel on the back of an iron plate, while the ribs *r* on the front are intended to present additional cooling surface to the air. Starting rheostats are not designed to carry current continuously, and should therefore never be used for regulating the speed of the motor. The resistance wire is made of such a size as to be capable of carrying the current for a short time only, usually 15 to 30 seconds, and if the current is left on continuously, the rheostat will be burned out. The handle *h* of the rheostat shown is provided with a spiral spring *s*, tending to hold it against the stop *a*, which makes it impossible to leave the contact arm on any of the intermediate points. On the last point a clip *c* is placed to hold the arm of the rheostat. Starting rheostats are made in a great variety of forms and sizes, but the object is the same in all of them, i. e., to provide a resistance that may be inserted when the motor is at rest and gradually cut out as the motor comes up to speed.

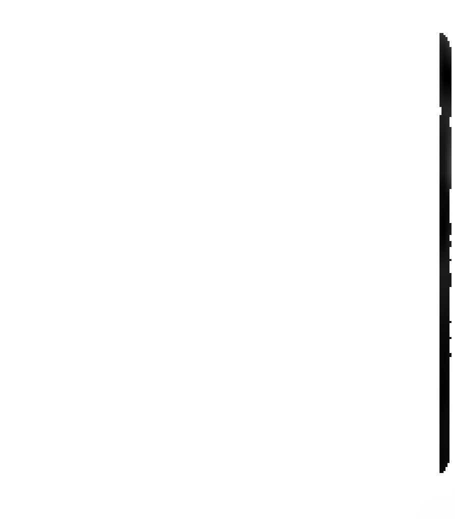


FIG. 19

SHUNT-MOTOR CONNECTIONS

52. One method of connecting a shunt motor to constant-potential mains is shown in Fig. 20. The lines leading to the motor are connected to the mains through a fuse block *D*, from which they are led to a double-pole knife switch *B*. A circuit-breaker is to be preferred to the fuse block, especially if the motor is a fairly large one. One end of the shunt field *F* is connected to terminal *1* of the motor, and one brush is also connected to the same terminal. The other field terminal is connected to the motor terminal *2*, and the other brush leads to the third terminal *3*.

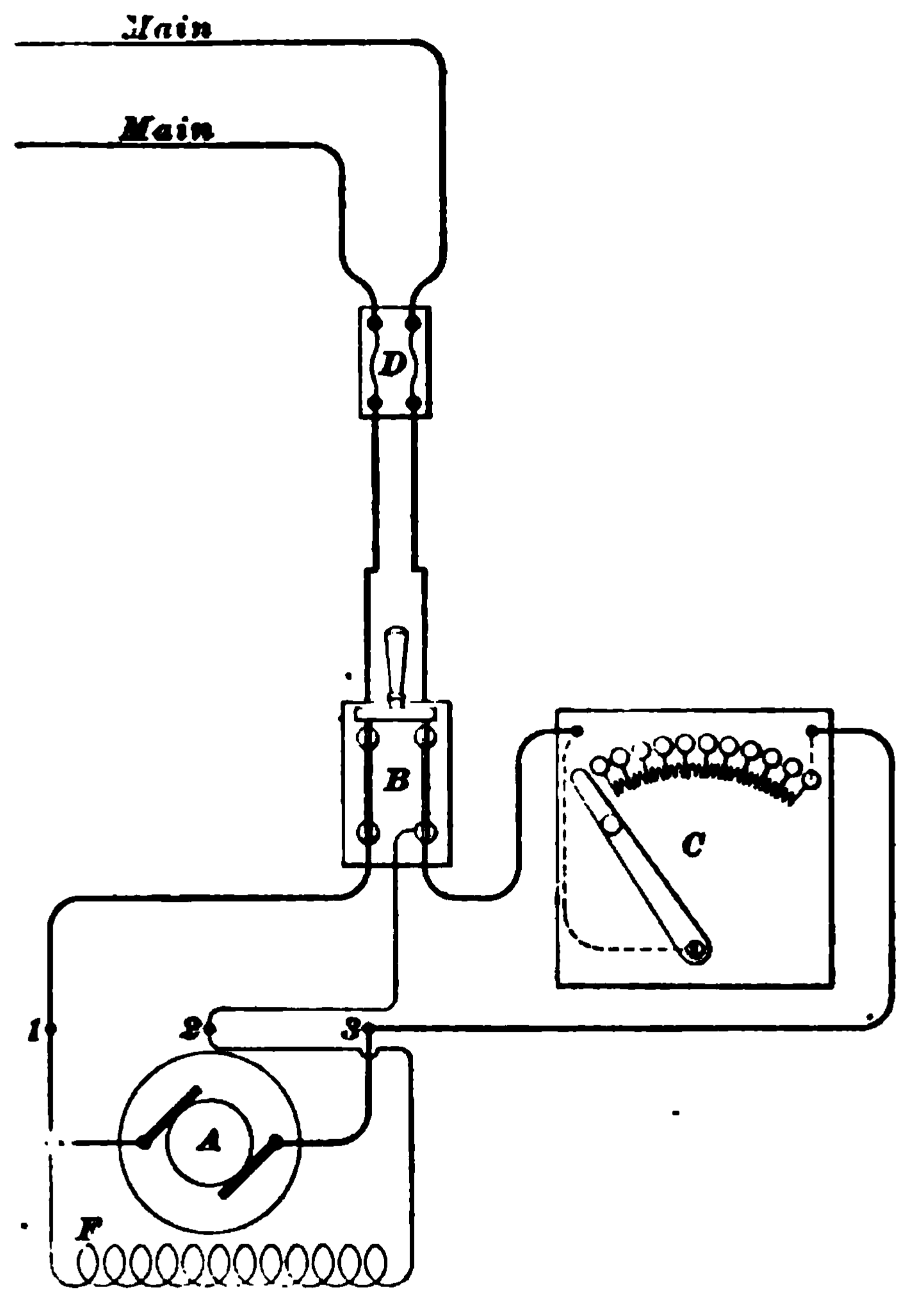


FIG. 20

One side of the main switch connects to terminal *1*; the other side connects to *3* through the starting rheostat *C*. Terminal *2* connects to the same side of the switch as the starting rheostat. It will be seen from the figure that as soon as the main switch is closed, current will flow through the field *F*. When the rheostat arm is moved over, current flows through the armature, and the motor starts up. The handle is then moved over slowly and left on the last point when the motor has attained its full speed.

53. In Fig. 20 one terminal of the field is connected to one of the brushes, and three terminals only are provided

on the motor. A motor connected in this way will always run in a certain direction no matter which line wires are connected to terminals *1* and *3*. Motors are now, almost without exception, provided with radial carbon brushes, and they can be run in either direction. It has become common practice, therefore, to provide them with separate field

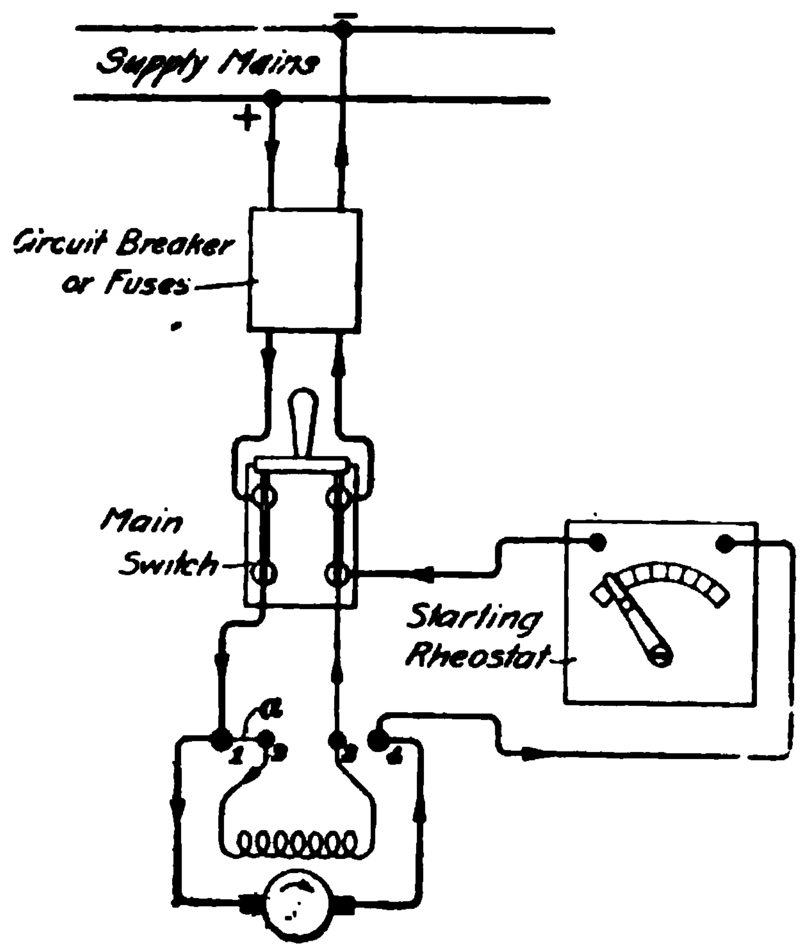


FIG. 21

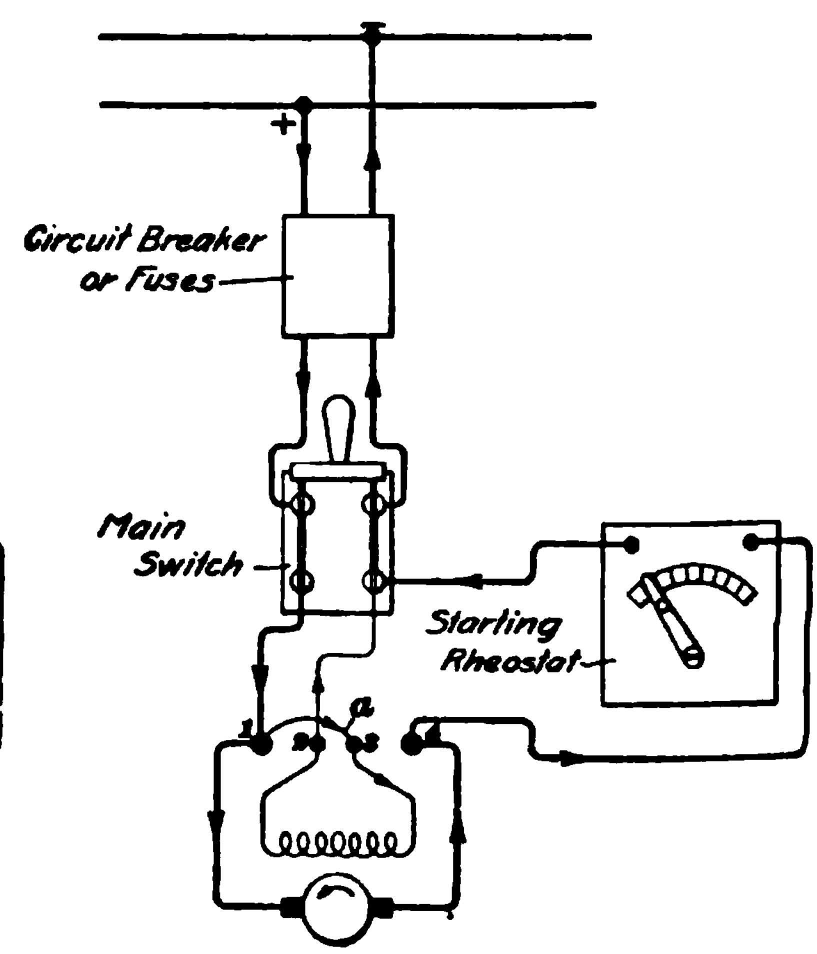


FIG. 22

and armature terminals, as shown in Fig. 21. By connecting field terminal *2* to armature terminal *1* by means of wire *a*, the motor will run, say, right-handed, as shown by the arrow. If it is desired to connect the motor for the reverse direction of rotation, it is easily done by joining terminals *1* and *3* and connecting field terminal *2* to the switch. This reverses the current in the field, as shown in Fig. 22.

54. Rheostats With Automatic Release.—In the preceding diagrams the simplest type of rheostat has been shown in order to make the connections as clear as possible. The simple starting rheostat shown in Figs. 19 and 20 is now used but little, for the following reasons. Suppose a motor is running and that the attendant shuts it

down by opening the main switch, but forgets to move the rheostat arm back to the off-position. When the motor is started again, the chances are that it will not be noticed that the rheostat is at the on-position, and when the main switch is closed a rush of current that may damage the motor takes place. Again, the motor may be running and the power may be thrown off the line for some reason or other, and when it is thrown on again, the rheostat is at the on-position and a rush of current takes place. For these

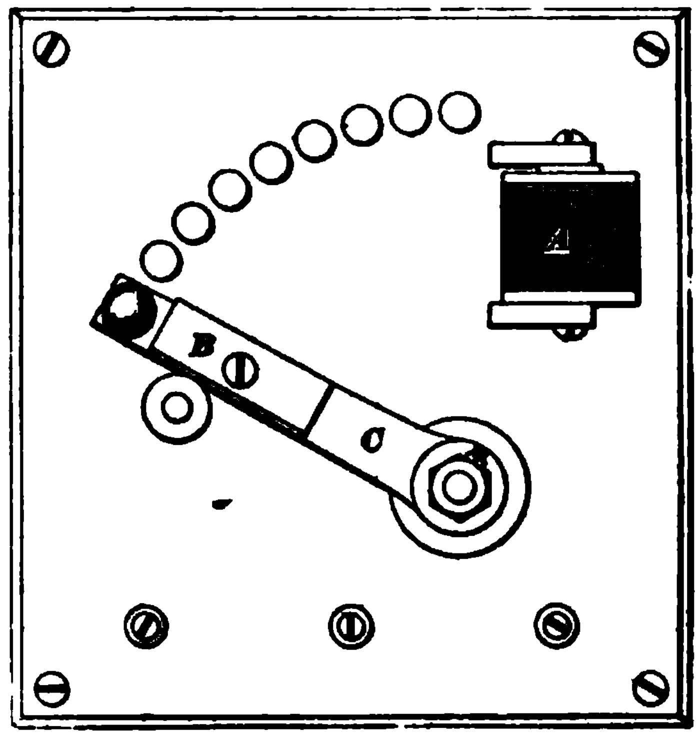


FIG. 23

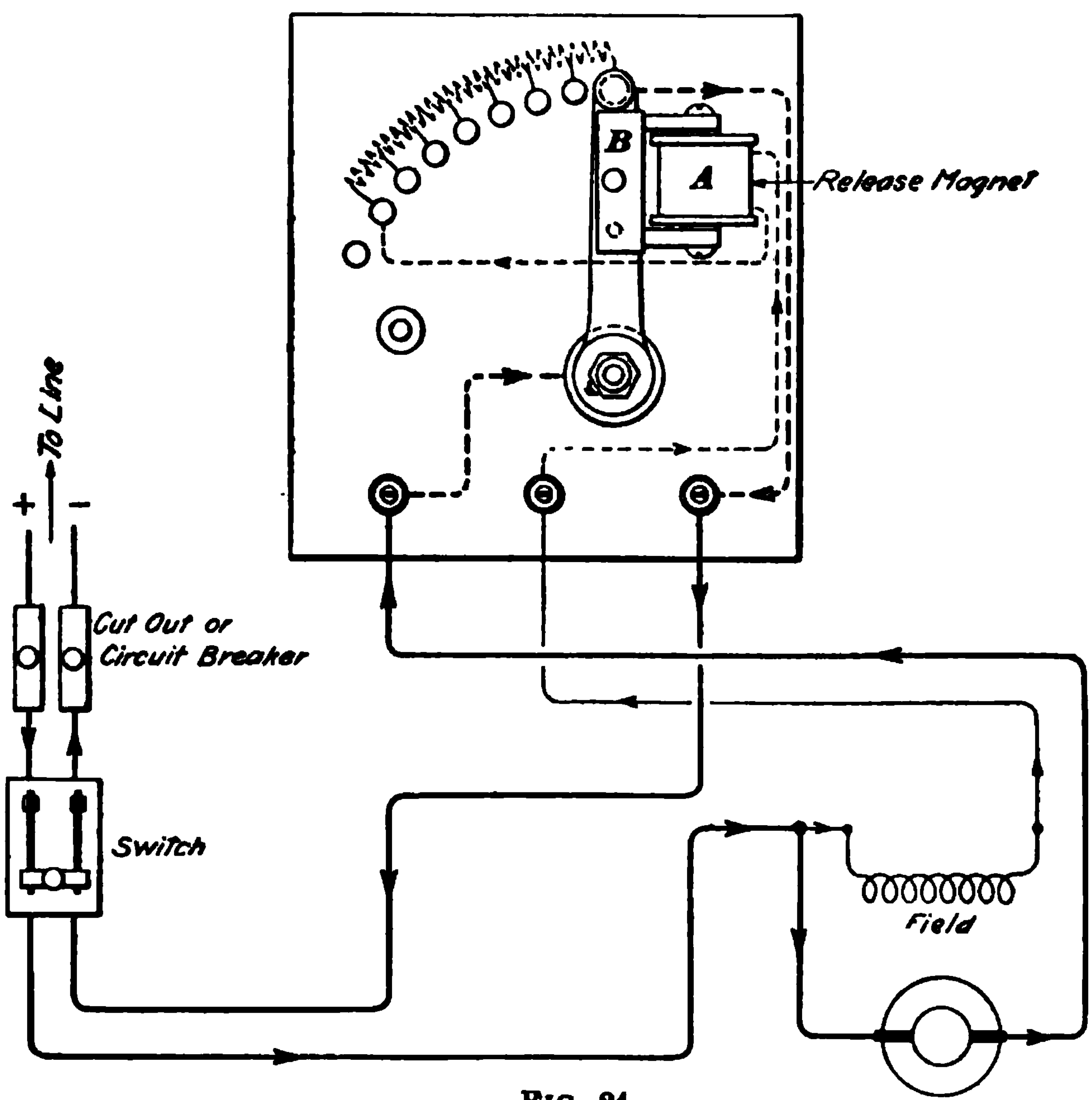


FIG. 24

reasons it is customary to install automatic rheostats that

will fly back to the off-position whenever the power is cut off from the motor, either by opening the main switch or by the power going off the line. Fig. 23 shows a simple form of automatic rheostat made by the General Electric Company. The automatic feature consists of an electromagnet *A* in series with the motor field. The lever *C* is moved over against the action of a coiled spring, and is held at the on-position by the attraction of magnet *A* for the armature *B*. Fig. 24 shows the rheostat connected to a motor. If the current supply is interrupted, the current in coil *A* gradually decreases as the motor slows up, and its pull becomes weaker, until finally the armature *B* is released, and the arm flies back to the off-position. The coil *A* is connected in the field circuit rather than in series with the armature, because it protects the motor in case the field circuit becomes broken. If the field circuit were broken and the armature left connected to the mains, a large rush of current would take place because the breaking of the field circuit would reduce the counter E. M. F. to practically zero.

55. Methods of Connecting Shunt Coil.—Practice differs in some respects regarding the connections for shunt motors. The difference lies in the method of connecting the shunt field. If the student will examine Figs. 20 and 24, he will notice that there is a difference in the connections of the shunt winding. The connections of Fig. 20 are equivalent to those in Fig. 25 (*a*), while those of Fig. 24 are shown in (*b*), Fig. 25. In (*a*) the shunt field is connected so that as soon as the main switch is closed, current flows through the shunt field. The field is therefore excited before current is allowed to flow through the armature by moving the rheostat to the first point. In (*b*) the field is not excited until the rheostat arm is placed on the first contact point. As the arm is moved over, the field current has to back up through the resistance, and when the arm is at the on-position, the starting resistance is in series with the field. On many boxes where this scheme of connections is used, an auxiliary contact *a* is arranged at

the end of the travel of the arm, so that the shunt current will not pass through the starting resistance when the motor is in regular operation; but even if this contact is not provided, the starting resistance is usually so low and the field current so small that its insertion in series has little appreciable effect on the operation of the motor. The chief advantage of the connections shown at (*b*) is that they

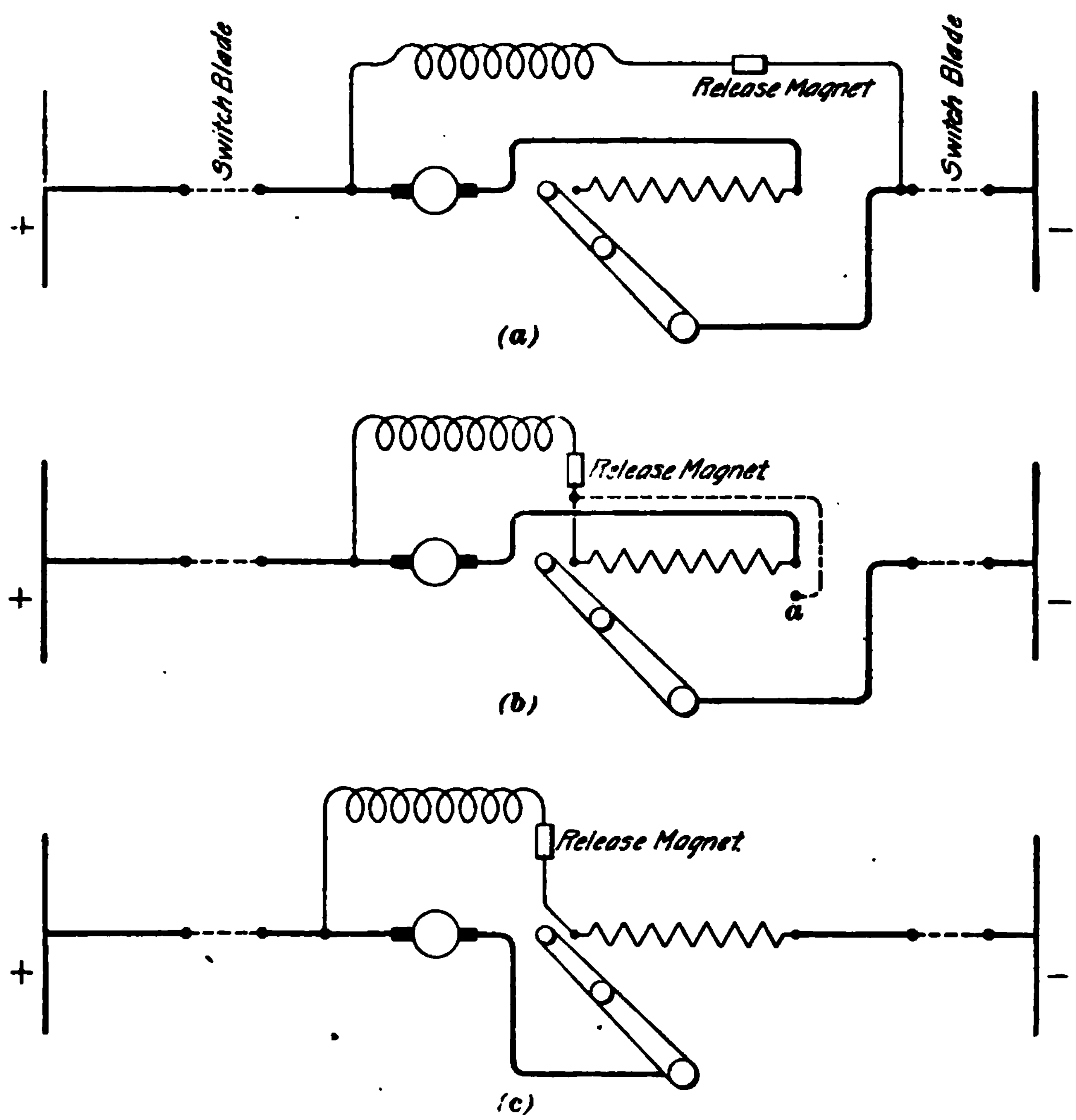


FIG. 25

avoid breaking the field circuit of the motor. As soon as the rheostat arm, Fig. 25 (*a*), flies back, the field circuit is opened. This always causes more or less of an arc and consequent burning action on the last rheostat contact, but a more objectionable feature is that the sudden stoppage of

the shunt current is liable to set up such a high induced E. M. F. in the windings that there is danger either of weakening or breaking down the field insulation. With the connection shown at (*b*) the field circuit is never broken; when the arm flies back there is scarcely any perceptible sparking and there is no strain on the field winding. The principal argument advanced in favor of the connections shown at (*a*) is that the field is fully excited before current is allowed to flow through the armature, and as it

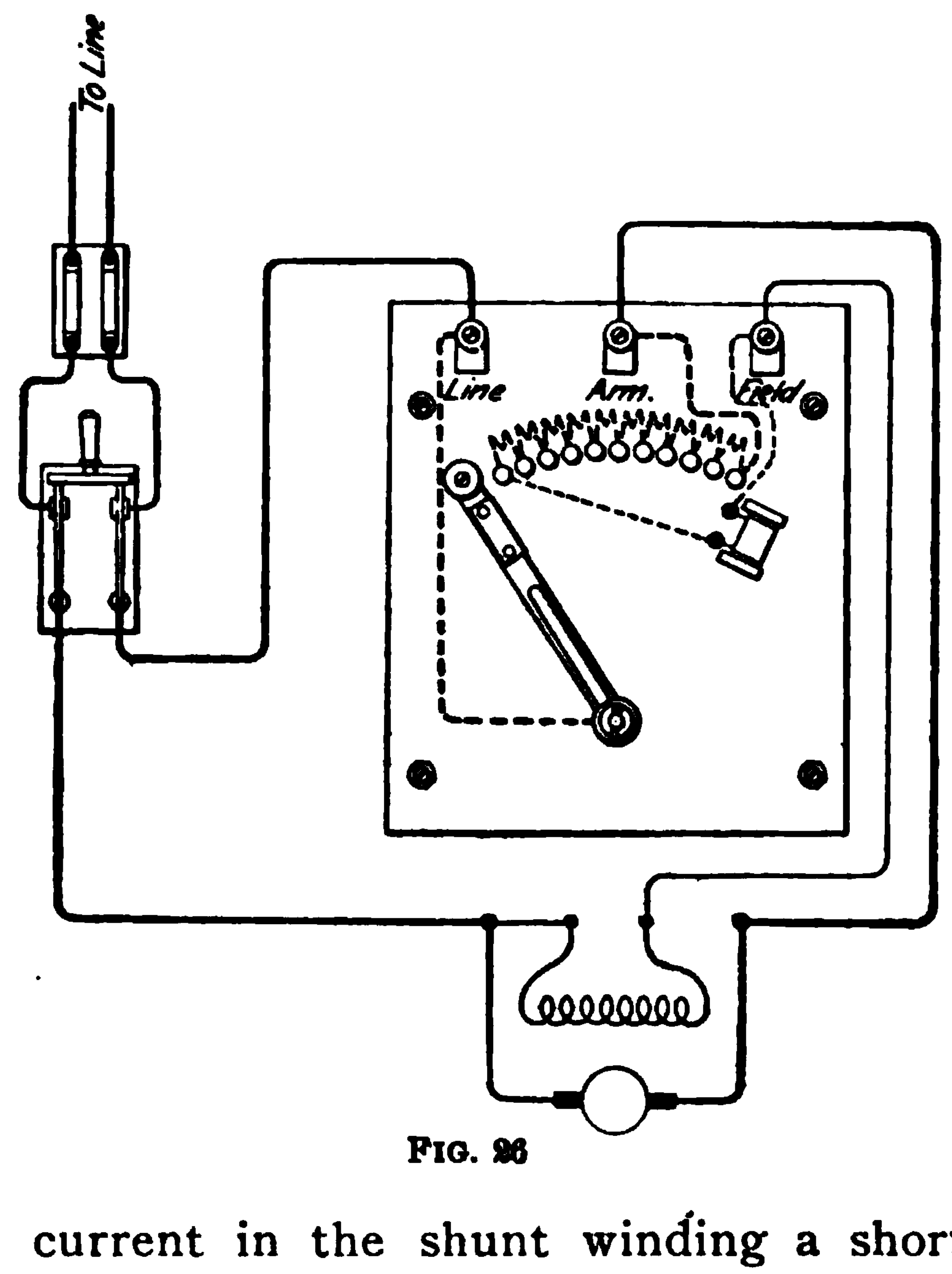


FIG. 26

takes the current in the shunt winding a short time to build up, a better starting torque is secured than when the connections (*b*) are used. This may be the case with large motors, but for motors of ordinary size, the time required for building up the field is so small as to be of little importance in this connection. Fig. 26 shows a Cutler-Hammer rheostat connected according to plan (*b*), which is the one used generally by the Cutler-Hammer Company on their shunt-motor rheostats.

56. Wrong Connection of Shunt Field.—Perhaps the most common mistake made when connecting up shunt-motor starting boxes is that shown in Fig. 27. This is the outfit for which the correct connections are shown in Fig. 26. The mistake consists in interchanging the heavy wires at the starting box, the line wire being placed in the armature binding post and the armature wire in the line binding post.

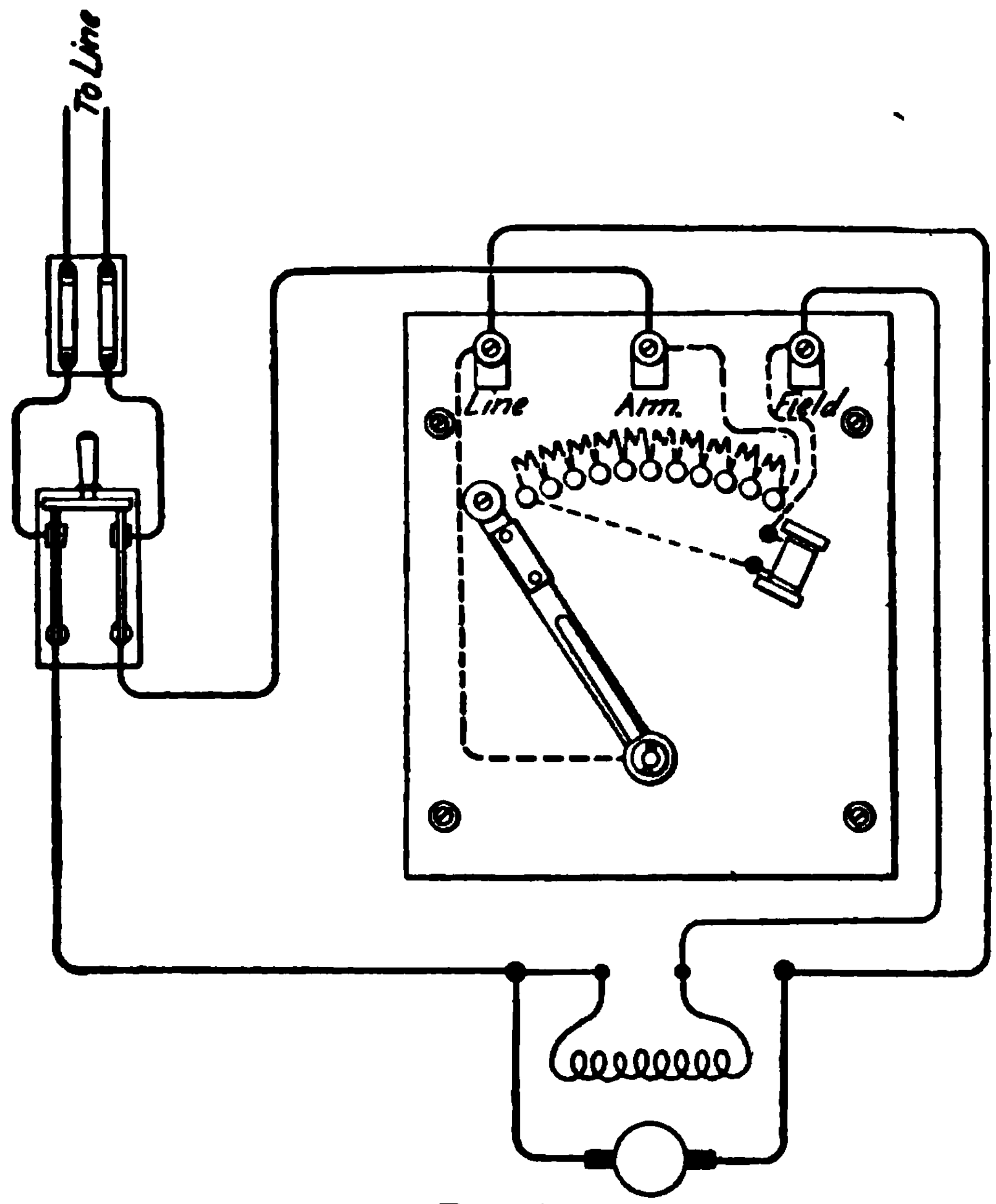


FIG. 27

Fig. 25 (*c*) shows these incorrect connections in a simplified form. As soon as the main switch is closed and the rheostat placed on the first point, the field is connected directly across the brushes, and the pressure applied to the field is therefore equal to the difference of potential between the brushes. Now, at starting, nearly the whole of the applied pressure is taken up in the starting resistance, and the only pressure across the field terminals is that due to the drop in the armature. The result is that the field is excited to but a very slight extent and the motor refuses to start. If the

rheostat arm is moved over, the current increases, and if it is moved far enough, may become sufficiently large to burn out the box. In some cases, if the load is not heavy, the motor may start up after the arm has been moved over a considerable distance, because the current may then become so great that the pressure across the brushes will excite the field enough to give the required torque. If, after connecting up a starting box, it is found that the motor does not start promptly on the first or second point, the connections should be carefully traced out to see that the above mistake has not been made. It is a very easy matter to get these wires confused, especially if they are run through conduit or bunched together in any way. This mistake is frequently made when the motor is situated some distance from the starting box, as the wires are then easily mixed.

57. Types of Automatic-Release Starting Rheostats.—Fig. 28 shows one of the smaller types of the Cutler-Hammer rheostat with automatic release. The connections

Fig. 28

Fig. 29

for this rheostat are shown in Fig. 26. Fig. 29 shows a General Electric starting rheostat with automatic release, and also provided with an overload attachment that causes

the arm to fly back to the off-position in case the current becomes excessive. Fig. 30 shows the connections for this box; it will be noted that it is connected according to Fig. 25 (*a*), the field being excited as soon as the main switch is closed. In Fig. 30 the rheostat arm is in the running position, all the resistance being cut out. By arranging the resistance as shown, the current flows across the contact arm and does not have to pass through the pivot. The contact arm is moved over against the action

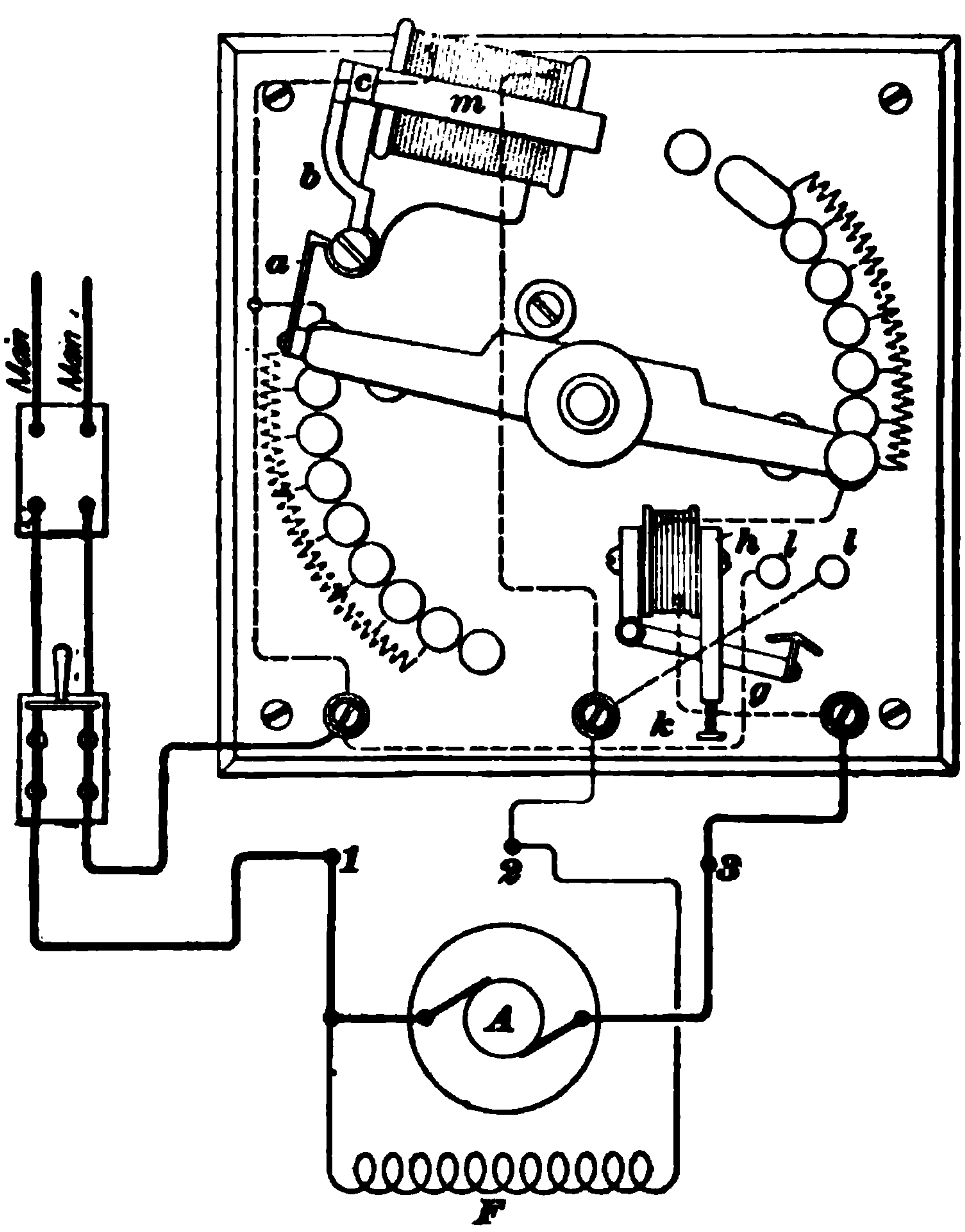


FIG. 30

of a spiral spring in the hub and is held in position by a catch *a* that fits into a notch in the hub of the lever *b*. This lever carries an armature *c*, which is held down by the release magnet *m*.

The device for protecting the motor against overloads consists of an electromagnet, the coil of which is connected in series with the armature *A*. This magnet is provided with a movable armature *g*, the distance of which from

the pole *h* may be adjusted by the screw *k*. When the current exceeds the allowable amount, the armature is lifted, thus making connection between the pins *l*. This connection short-circuits the coil of the magnet *m* and the lever goes to the off-position.

58. The design of a starting rheostat depends very largely on the size of the motor with which it is to be used, since heavy currents require large contact surfaces and heavier construction throughout. Speed-regulating rheostats are constructed in much the same manner as starting rheostats, the only difference being that the regulating rheostat is much larger, so as to stand continuous use without overheating.

REVERSING DIRECTION OF ROTATION

59. It has already been mentioned that if the current in either the field or armature of a motor be reversed, the direction of rotation will be reversed. This is evident from an inspection of Figs. 2 and 3. If the current in wire *a* be reversed while the field is left unchanged, the direction of motion will be reversed. Also, if the direction of the current in the wire is left unchanged, and the field reversed, the direction of motion will be reversed. If both current and field be changed, the direction of motion will remain unchanged.

60. A series motor will run in the same direction, no matter which of the supply lines is connected to its terminals *a*, *b*, Fig. 31. Reversing the line connections simply reverses the current through both armature and field, and does not therefore change the direction of rotation. In order to reverse the motor, either the armature terminals *c*, *d* must be interchanged, so as to reverse the current through the armature, or the terminals *d*, *b* must be interchanged, so as to reverse

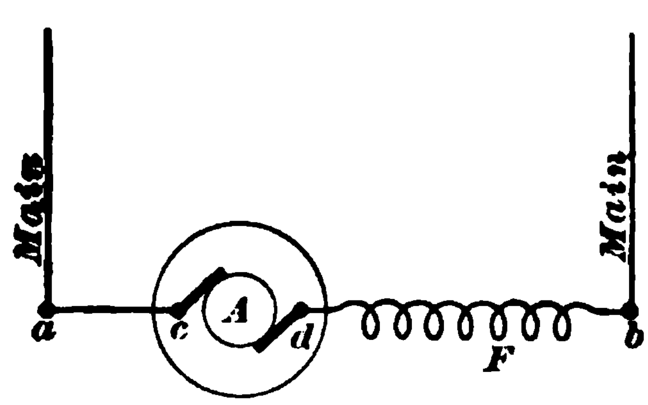


FIG. 31

the current through the field. In street-railway work the motors are usually reversed by reversing the current through the armature, the current through the field remaining unaltered.

When it is desired to reverse a motor while it is running, it is very necessary to insert a resistance in the armature circuit before reversing the current through the armature. It must be remembered that the counter E. M. F. which the motor was generating just before reversal becomes an active E. M. F. and helps to make the current flow through the armature as soon as the current is reversed, and this action continues until the motor starts to turn in the opposite direction. It is best, therefore, when possible, to let the motor drop considerably in speed, or even come to a standstill, before reversing it.

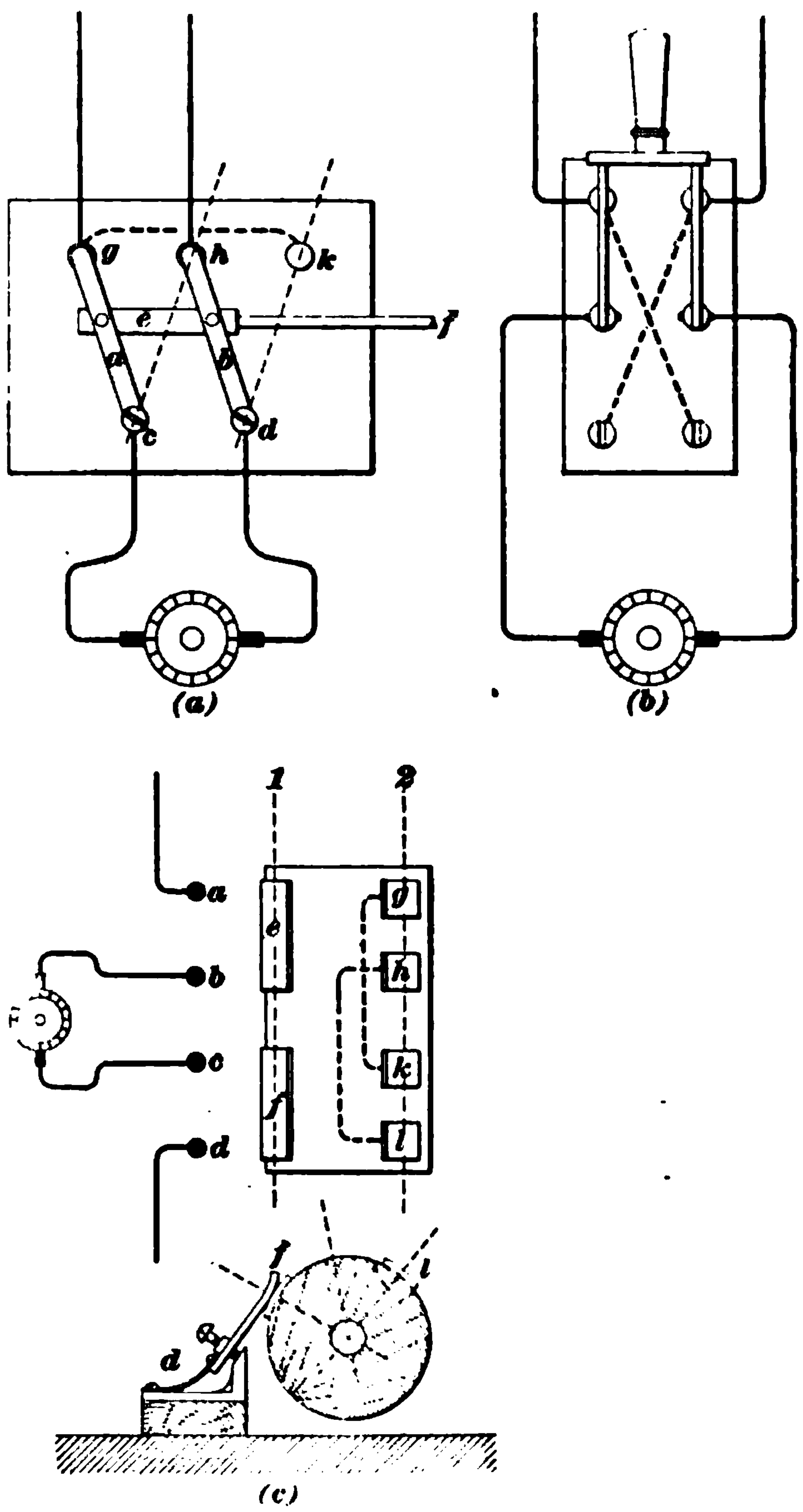


FIG. 32

61. Reversing Switches.—In order to reverse the current in a motor armature so as to bring about a reversal of rotation, a **reversing switch** is placed in the armature circuit. Fig. 32 shows three common types of switch. That shown

at (*a*) consists of two metal blades *a*, *b* hinged at *c d* and connected together by an insulating cross-piece *e*. The blades can be moved from the position shown in the figure to that indicated by the dotted lines, by pulling on the rod *f*. In one position, *c* and *d* are connected to *g* and *h*, while in the other position they connect to *h* and *k*, thus reversing the current in the armature. Fig. 32 (*b*) shows an ordinary double-pole double-throw knife switch used as a reversing switch. The middle clips are connected to the armature, and the top and bottom clips are cross-connected, so that when the switch is thrown up, the current in the armature is in one direction, and when it is thrown down, the armature current is reversed. The reversing switch shown at (*c*) is of the cylinder type, and is used very largely for street-car controllers. The upper sketch shows the cylinder and indicates the arrangement of the contacts. Contact fingers are connected to terminals *a*, *b*, *c*, *d*, as shown by the end view in the lower sketch. Contact pieces *e*, *f*, *g*, *h*, *k*, *l* are mounted on a wooden drum that can be rotated through an angle sufficient to bring the fingers in contact with either set of plates. When the fingers rest on plates *e* and *f*, as indicated by the dotted line *1*, the current entering at *a*

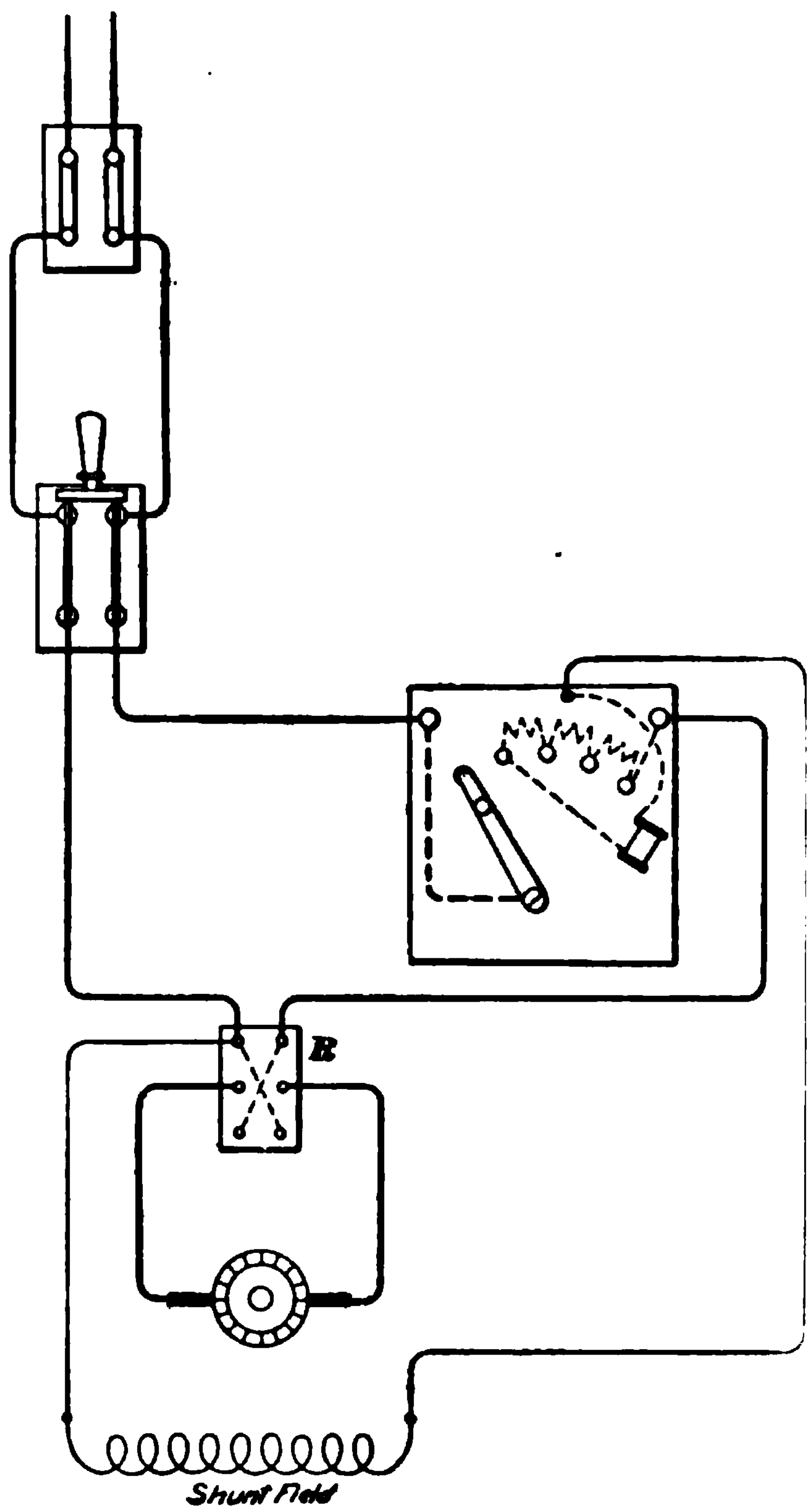


FIG. 33

takes the path *a–c–b* through armature *c–f–d*. When the drum is turned so that the fingers rest on the other contacts, as indicated by the dotted line *2*, the path becomes *a–g–k–c* through armature in the reverse direction *b–h–l–d*.

62. Shunt Motor With Reversing Switch.—Fig. 33 shows connections for a shunt motor with reversing switch *R*. The field is excited from the mains as soon as the rheostat is placed on the first point, and remains excited in the same direction regardless of the position of the reversing switch.

63. Fig. 34 shows a Cutler-Hammer reverse starting rheostat. When the motor is not running, the handle *h* is

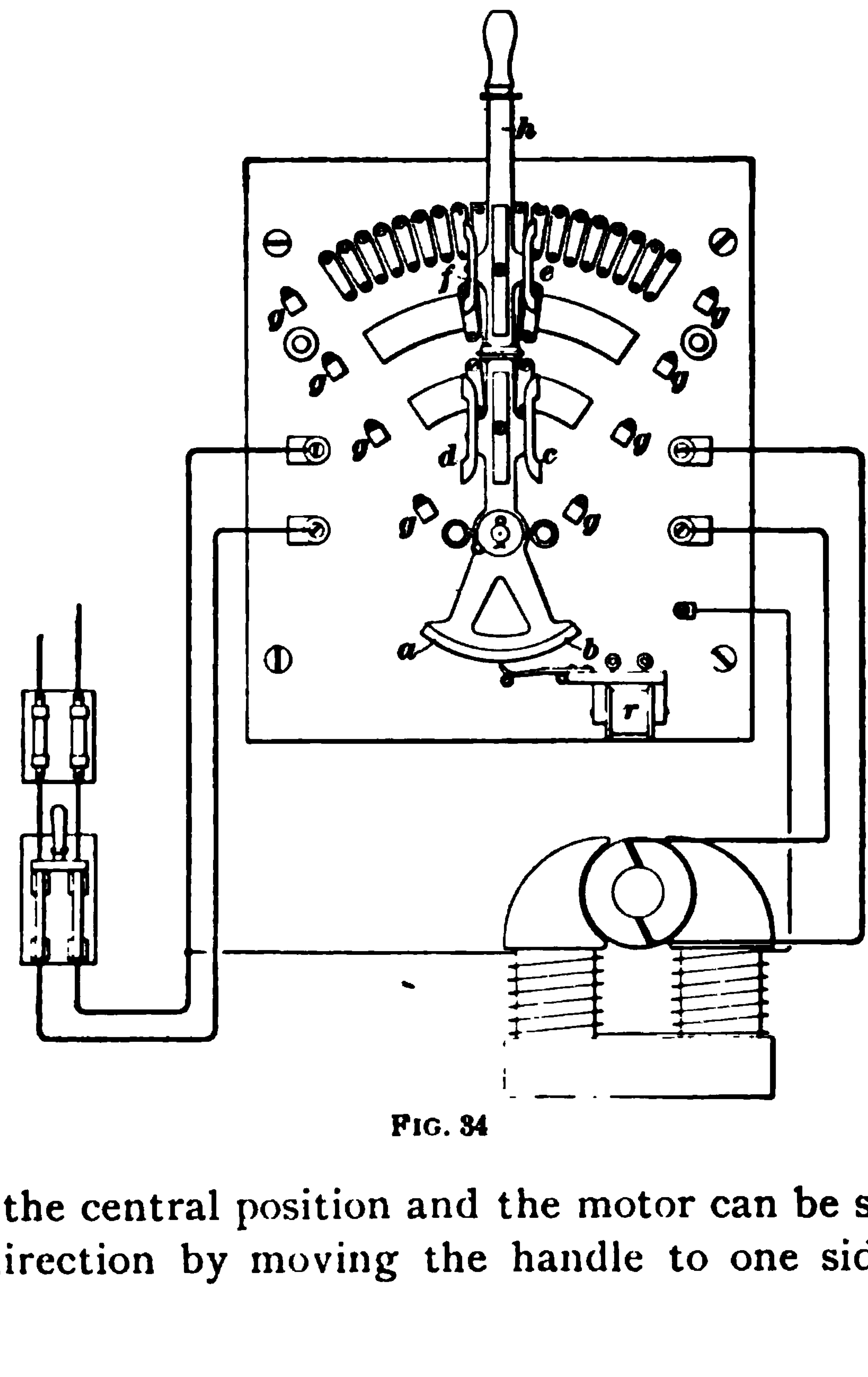


FIG. 34

held at the central position and the motor can be started in either direction by moving the handle to one side or the

other, thereby changing the direction of the current in the armature circuit. The arm is held at the on-position by the catch on the end of the armature of the release magnet *r* engaging with the notches *a* or *b*. This starter is provided with auxiliary laminated contacts *c*, *d*, *e*, *f*, which press against the studs *g*, *g*, thus giving a good contact for carrying the current continuously after the motor has been started. Shunt motors are always reversed by reversing the current in the armature, because it is not advisable to interrupt or reverse the shunt field current on account of the high induced E. M. F.'s that are liable to be set up.

SERIES-MOTOR CONNECTIONS

64. The connections for series motors are on the whole simpler than those for shunt motors. Since the field is

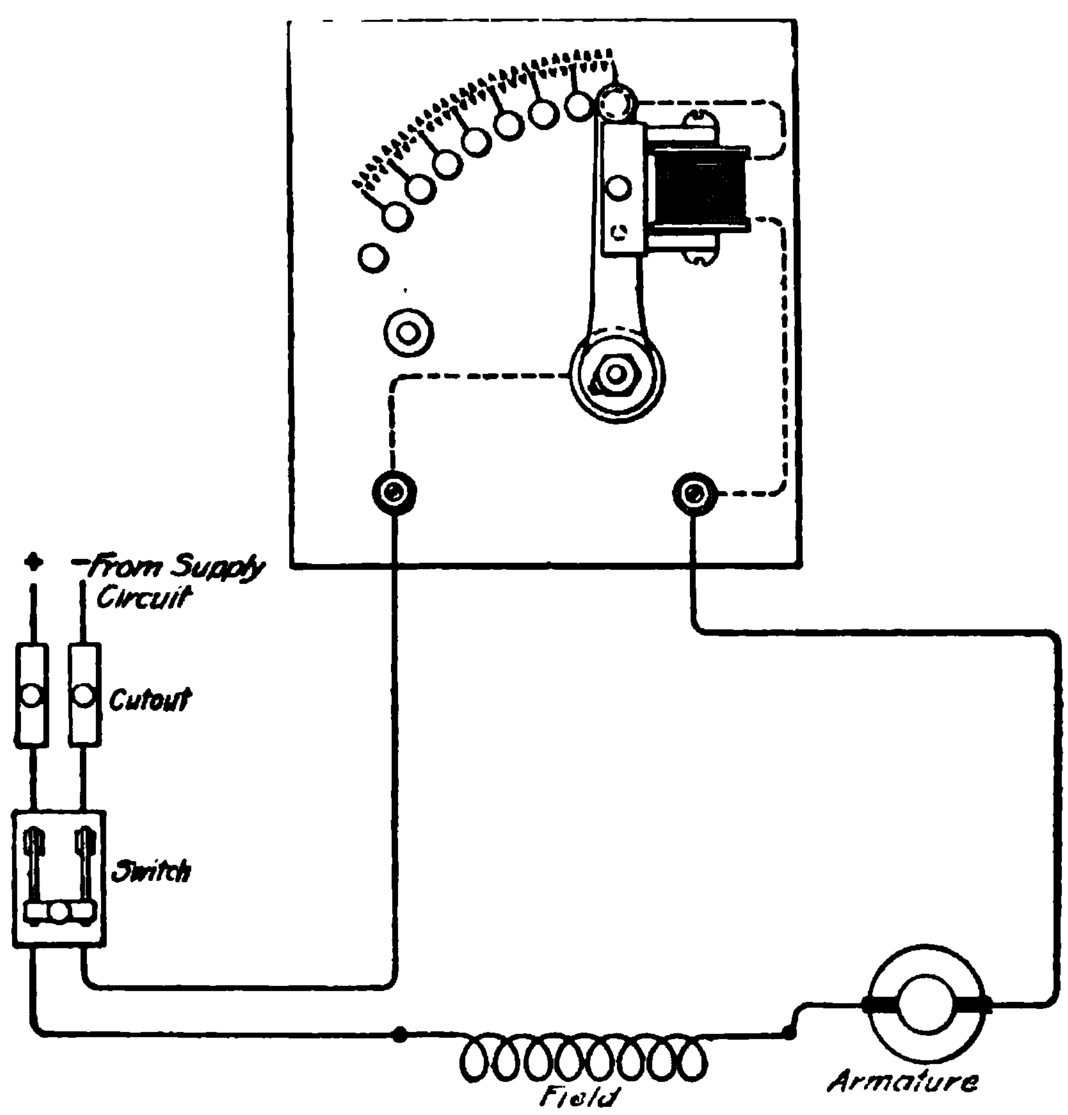


FIG. 35

in series with the armature, and helps to choke back the current at starting, a series motor does not require as large

a starting resistance as the shunt motor. Fig. 35 shows a simple series-starting rheostat and connections.

For motors that have to be stopped, started, and reversed frequently, special types of starting devices are used. These are generally called *controllers*. For street-railway work these controllers become quite complicated, as they are designed not only to cut resistance in or out, but also to make various combinations of the two or more motors used on a car. A full explanation of these controllers will be found in *Electric Railways*, so they will not be considered here. Controllers somewhat similar to those used on street cars are also used for stationary work, but when so used they are generally required to control but one motor, and hence are designed to simply cut resistance in or out and not make series and parallel combinations. Fig. 36 shows a series motor equipped with an ordinary starting box and reversing switch *R*.

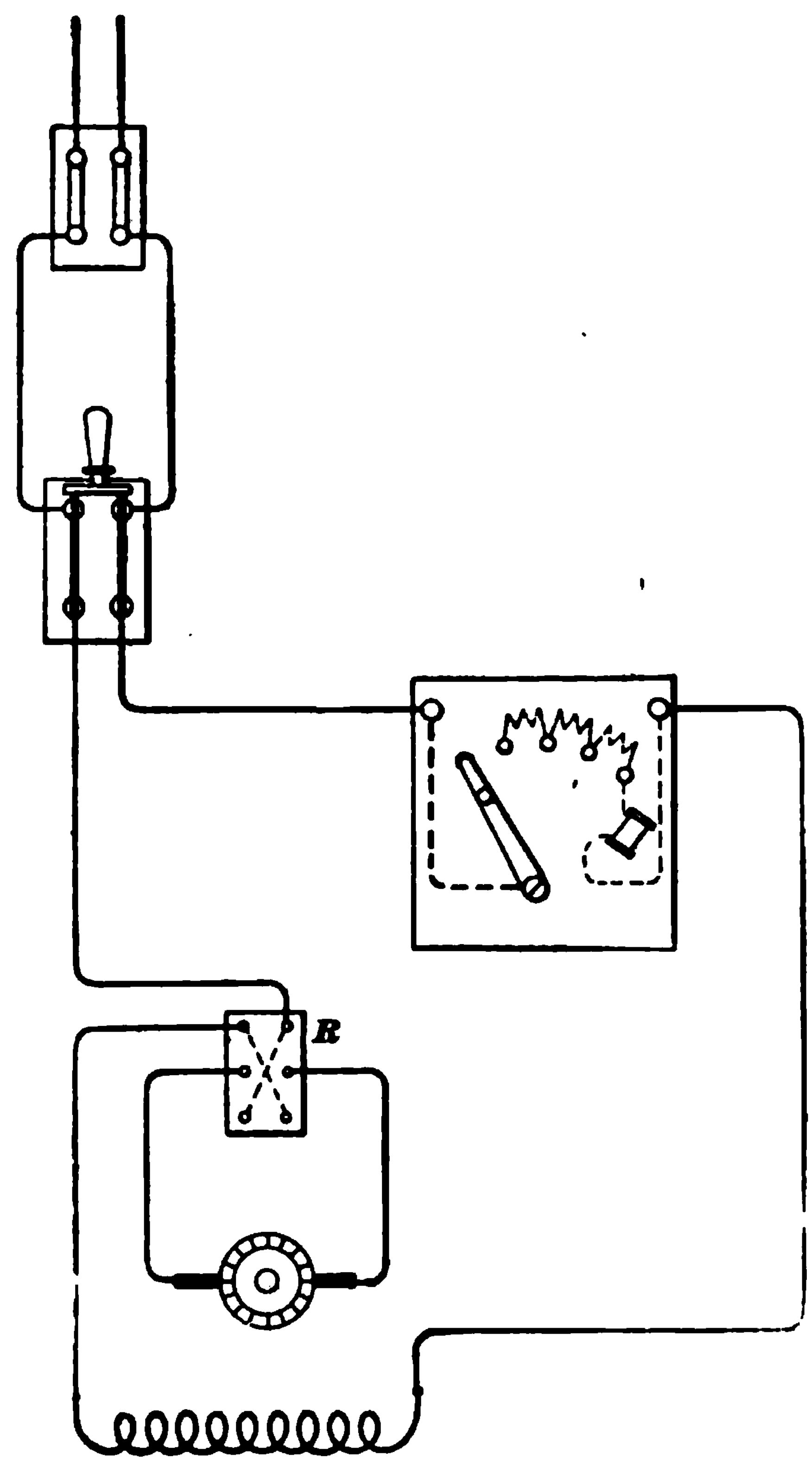


FIG. 36

65. The series-motor, as already stated, is used very largely for operating traveling cranes, hoists, rolling-mill machinery, etc. The use of these motors in rolling mills and other places calling for heavy service has resulted in the

development of a large number of controlling devices specially adapted to work of this kind. For such service the

(c)

(b)
Fig. 27

(a)

motor must be capable of being stopped, started, and reversed quickly, and the controller must be of simple and

substantial construction. Fig. 37 shows three views of a controller that is used in a large number of steel mills and other plants for the operation of cranes, etc. It is known as the Dinkey controller, manufactured by the Electric Controller and Supply Company, of Cleveland, Ohio. The resistance coils and contact switch are mounted together,

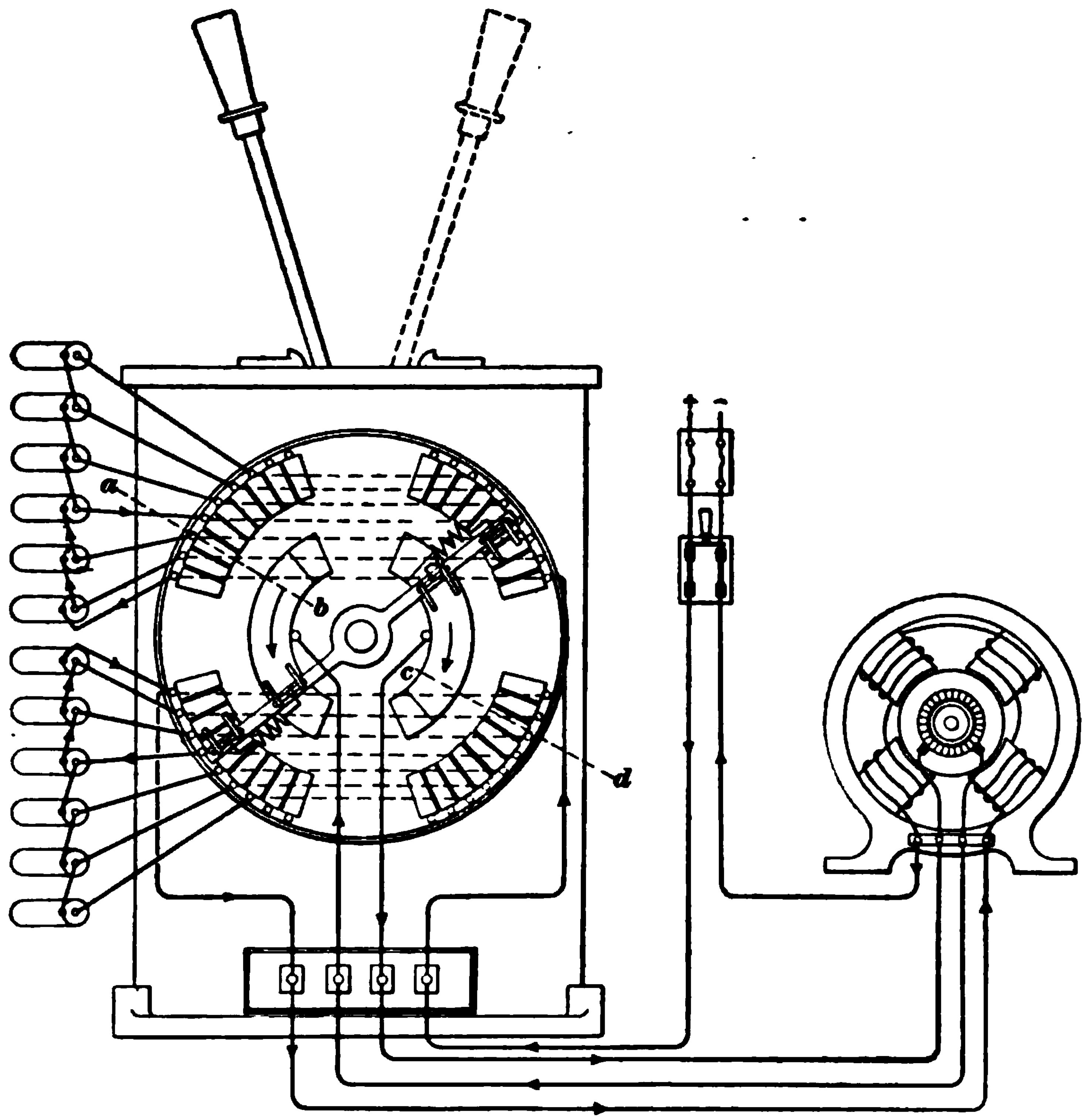


FIG. 38

so that there are but four terminals to the controller, and it can therefore be easily disconnected and replaced in case of trouble. The resistance coils *a*, Fig. 37 (*c*), are wound on heavy asbestos tubes and mounted as shown. The terminals *b* of the resistance connect to the brass lugs to which the drop-forged copper contacts *c* are screwed, view (*a*). When

the motor is at rest the operating handle d occupies the vertical position; a forward movement of the handle rotates the arm e, view (a), and causes the motor to run in one direction; a reverse movement of the lever reverses the rotation of arm e and makes the motor run in the opposite direction. The contact switch, therefore, serves both to gradually cut out the resistance and also to reverse the motor. The arm carries four sets of contacts f, g, h, and k, insulated from it; the inner contacts g and h bear on the contact arcs l, m, which are provided with renewable tips o, p. When the controller is at the off-position, the contacts rest on the insulating pieces r, r, r, r. Contacts f and g, and h and k are connected together by the coils s, s, so that the current passes through these coils and sets up a magnetic field in the region of the contacts. The object of this field is to suppress sparking at the contacts; as soon as an arc is formed, it is forced out or blown out by the magnetic field.

66. Fig. 38 shows the connections. The upper and lower left-hand sets of contacts are connected to the two groups of resistance coils, and the right-hand contacts are connected across to the similar contacts on the left, as indicated by the horizontal dotted lines. When

Fig. 39

the operating lever is in the full-line position, the current flows as shown by the arrowheads, but when thrown over to the dotted position, the current through the armature is reversed, while that in the field remains the same, thus reversing the direction of rotation. This can be readily seen by tracing the path of the current when connection is made between the contact arcs and segments as indicated by the dotted lines *a b*, and *c d*.

67. Fig. 39 shows another style of electric-crane controller made by the same company. It is similar in principle to the one just described, the only difference being that the four sets of contacts are mounted on two vertical parallel slate bases, instead of on a single base, as in Fig. 38.

(*a*) (*b*)

FIG. 40

68. Fig. 40 (*a*) shows a front view of a smaller type of controller made by the Electric Controller and Supply Company. It is intended for lighter work than the two

previously described, and will handle motors up to 17½ horsepower at 500 volts. Fig. 40 (*b*) shows a rear view of the

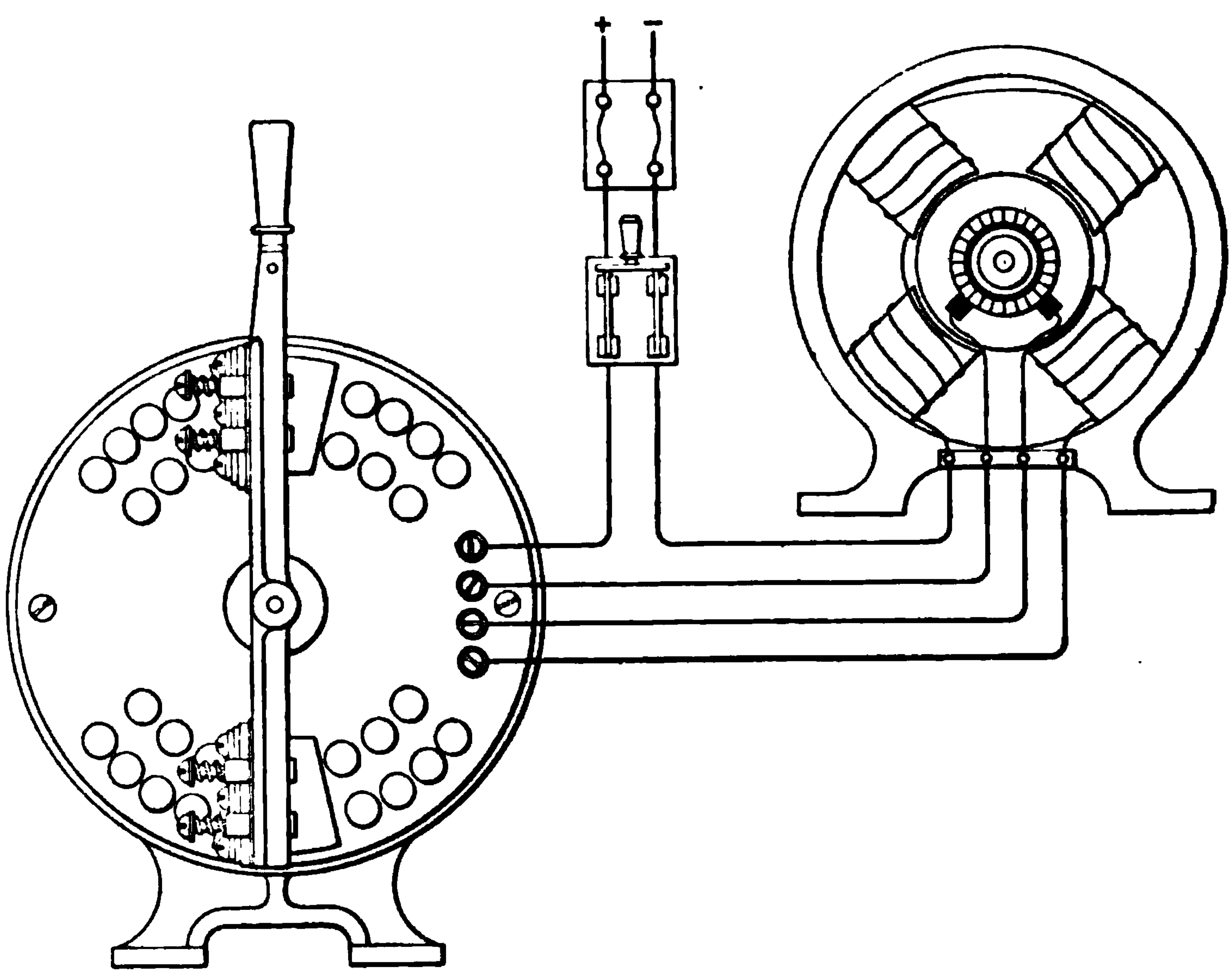


FIG. 41

slate face with the resistance coils in place. Fig. 41 shows the method of connecting one of these controllers to a series motor.

AUTOMATIC STARTING RHEOSTATS

69. Sometimes it is necessary to have a starting rheostat arranged so that it can be controlled from a distant point, in which case the box has to cut out the resistance automatically. The most common method of accomplishing this is to provide the rheostat with a solenoid which, when energized, moves the contact arm and cuts out the resistance.

70. Fig. 42 shows a Cutler-Hammer automatic starter. In this case it is used to control a motor that operates a

pump supplying water to a tank. When the solenoid *a* is energized, it draws up its core and thus moves the arm *b* over the contacts. The motion is controlled by a dashpot *c* filled with oil, so that the arm is drawn slowly over the contacts. The controlling switch at the distant point is shown at *d*, and in this case the switch is opened and closed by a float. When *d* closes, the solenoid switch *e* operates, thus

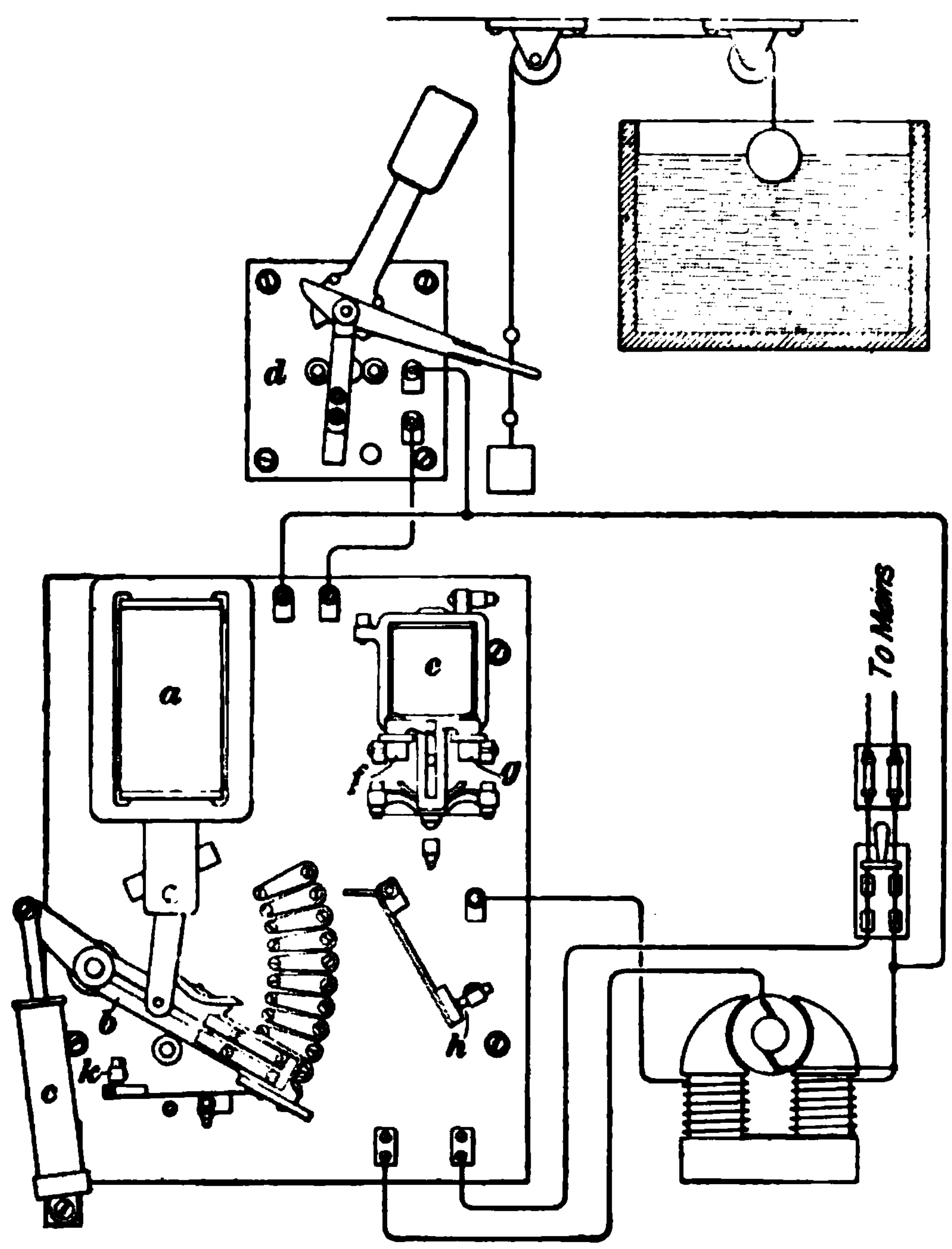


FIG. 42

raising its core and making contact between studs *f*, *g*. This closes the main circuit. Solenoid *a* is energized at the same time, and the resistance is gradually cut out, thus starting the motor. When the core of *a* reaches the upper position, the carbon points at *h* are separated, thus placing a lamp in series with *a* and preventing its overheating. When the core has reached its upper position, a small current is sufficient to hold it there. After *e* has closed and

arm *b* has moved from its lowest position, the carbon points at *k* separate, thus placing a lamp in series with *c*. Placing lamps or other resistance in series with the solenoids not only prevents heating, but also effects a saving in current.

71. In the case of automatic controllers designed for large currents, it has been found that the sliding-contact method gives more or less trouble due to roughing up of the contacts, and that the arm sometimes sticks instead of returning to the off-position when the current is shut off. This is especially the case with controllers for electric elevators where the starting and stopping is very frequent. In order to do away with sliding contacts, a type of controller of which Fig. 43 is an example is now largely used for this class of work. It consists of a number of automatic switches, each section of the resistance being cut out by an individual switch. Each switch consists of a solenoid which

FIG. 43

when energized raises its core and brings the disk d' mounted thereon into contact with the fingers f, f'. In this controller the switch C' closes the main circuit, while A' and B' control the motion of the elevator up or down, that is, A' and B' are reversing switches. The smaller solenoids control the various sections of the resistance and, as compound-wound motors are used for elevator work, also cut out the series-field when the motor has attained full speed. The main fuses are at k k, and the resistance is mounted in a separate case behind the controller. The contact fingers are provided with auxiliary carbon tips x, x, at which the break takes place. The disks are free to revolve, so that whatever burning action there may be is distributed around the whole disk, and there is therefore little danger of sticking.

MULTIVOLTAGE SPEED CONTROL

72. As previously pointed out, the speed of a motor may be controlled by varying the E. M. F. applied to the armature, and the simplest way of doing this is to insert a resistance in series with the armature. For some classes of work a wide range of speed control is necessary. For example, in machine shops and printing plants this is the case. One great objection to the rheostatic method of control, outside of its wastefulness, is that a change in speed occurs with every change in load. Suppose the motor is carrying a given load and that the rheostat is set at a point where the required speed is obtained. Now, if the load is increased, the current will increase, and the drop in the rheostat will also increase, thus cutting down the E. M. F. at the armature terminals and decreasing the speed. In the same way a decrease in load will cause an increase in speed. In order to overcome the disadvantages of rheostatic control, a number of so-called **multivoltage systems** have been devised. As a rule these systems are intended for those places where a number of motors have to

be operated at variable speed, because they are too expensive to install for single motors except in some special cases. This method of control is sometimes known as the Leonard system, on account of the patents relating to it having been taken out by Mr. H. Ward Leonard.

73. Fig. 44 shows a simple case of multivoltage control. The dynamo *A* supplies current to the motor *B*. Current is supplied from the constant-potential mains *C* to the fields *D* and *E* of the dynamo and motor. The motor field receives a constant excitation, but that of the dynamo can be varied by means of a field rheostat *F*. It is evident that by varying the field excitation of the dynamo, the pressure applied to the motor can be varied through a wide

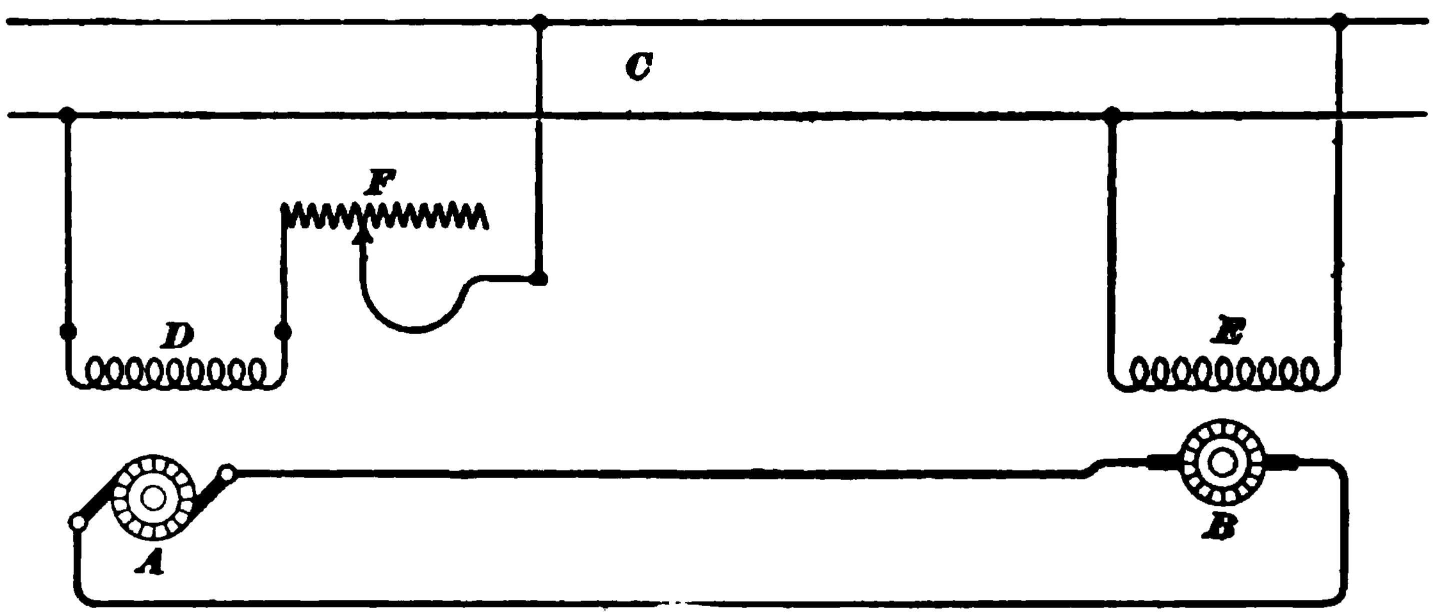


FIG. 44

range, and since the motor field excitation is constant, a correspondingly large range in speed can be obtained. This method, therefore, allows the voltage applied to *B* to be varied without the insertion of resistance between *B* and *A*. For each voltage of *A* there will be a definite speed of *B*, and this speed will remain practically constant no matter what load *B* is called on to carry.

74. The method shown in Fig. 44 is not generally applicable, because it requires a dynamo for each motor, and this is out of the question, except, perhaps, in a few special cases. However, by using a special generating equipment, a sufficient number of voltages can be obtained

to give the necessary range in speed. Fig. 45 shows a multivoltage system that is well suited for the operation of machine tools. *A*, *B*, and *C* are three armatures generating voltages of 110, 80, and 60 volts, respectively. The armatures may be mounted on the same shaft, and each provided with its own field magnet; they may be three separate machines, or what is more usual, *A* may be a standard 110-volt dynamo and *B* and *C* the commutators of a double-voltage dynamo, i. e., a dynamo having a single field and an armature provided with two windings connected to two separate commutators. The Bullock Electric Manufacturing Company make apparatus for this system, and recommend the above voltages as suitable for machine-shop

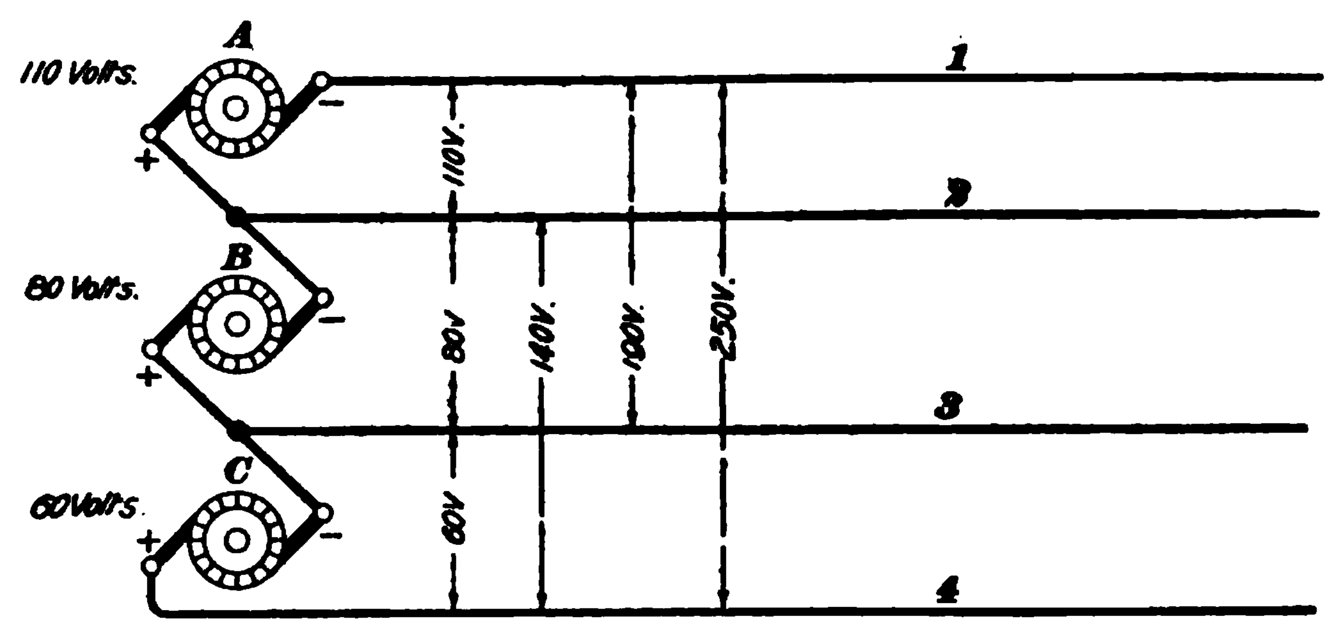


FIG. 45

operation. The dynamos excite their own fields, and the armatures are connected in series, as shown. Four wires *1*, *2*, *3*, *4* are run to each motor, and the pressures obtained between the various lines are as indicated. Ordinary shunt-wound motors may be used, their fields being excited by connecting them across any pair of the wires, say, across *1* and *2* or *1* and *4*, since 110 and 250 are standard voltages. By means of a suitable controller, the armature terminals can be connected between any pair of wires, so that the applied voltage can be any one of the following: 60, 80, 110, 140, 190, 250. This will give six different speeds, and the speed corresponding to each voltage will remain constant no matter how the load on the motor may vary. If

intermediate speeds are desired, they can be obtained by means of a rheostat in the motor field.

75. Fig. 46 shows a multivoltage system with a special generating outfit consisting of the two armatures *A* and *B* mounted on a common shaft. Armature *A* has two windings, one of which generates 60 volts and the other 90 volts. *B* generates 110 volts. The armature of the motor is connected to a controller, represented diagrammatically in the

Speed Regulating Rheostat

FIG. 46

figure by the two switches S, S', by means of which the armature can be connected across any pair of lines. The field is excited from the 110-volt mains and has a rheostat in series with it to admit of intermediate changes in speed.

76. Fig. 47 shows a multivoltage system where a main 110-volt generator *A* supplies current for lighting purposes and constant-speed motors. In order to take care of the variable-speed load, a motor generator set *B C* is installed.

It is usually sufficient for this set to have a capacity about 20 to 25 per cent. of the rated horsepower of the variable-speed motors, because most of the motors are, as a rule, operated at slow speed for a portion of the time only. Motor *B* drives the double-voltage generator *C* and thus renders available six different voltages. An ordinary

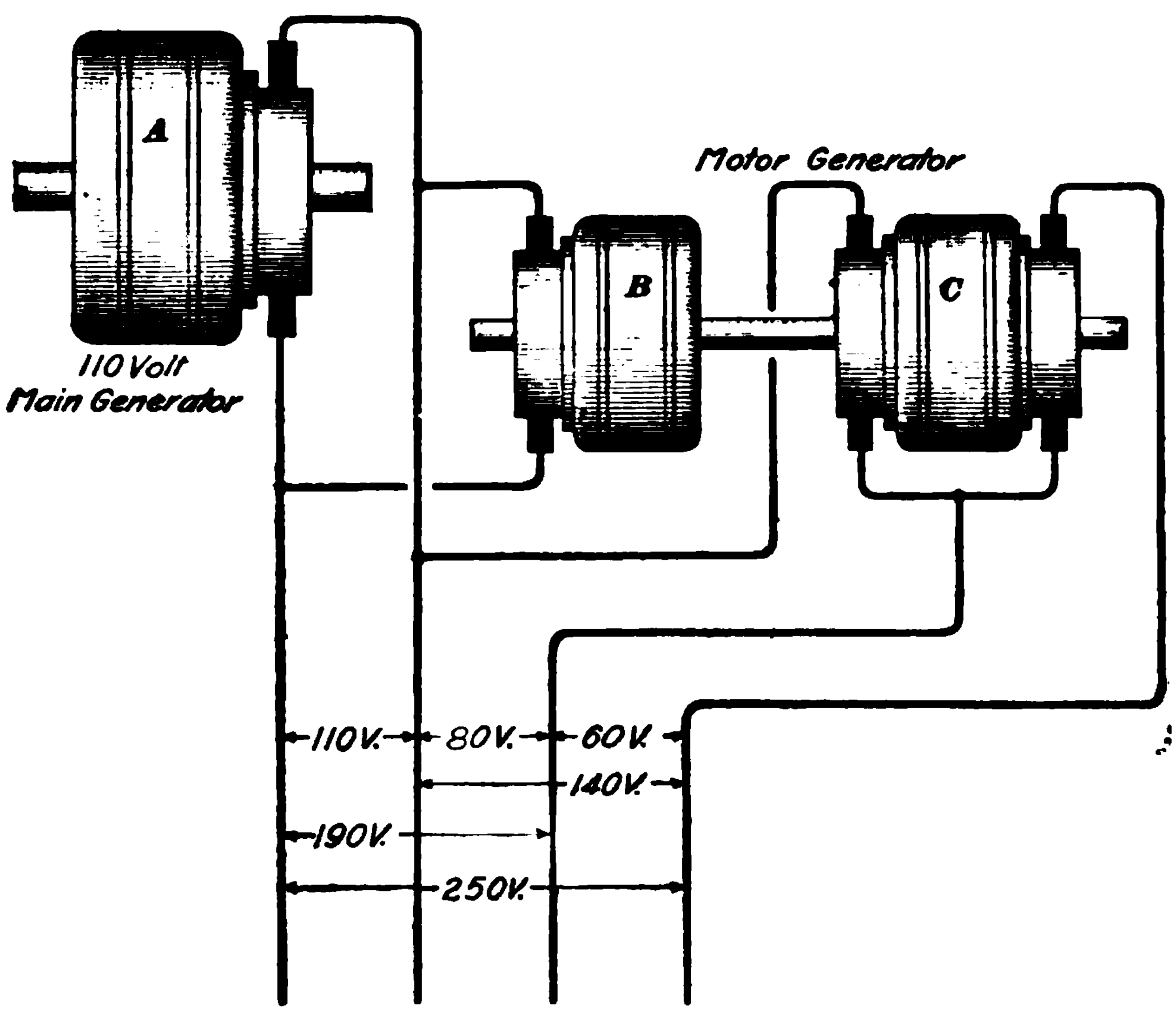


FIG. 47

110-volt distributing system can therefore be converted into a multivoltage system by the addition of a motor generator set as described. Fig. 48 shows another arrangement, where the main generator is a 220-volt machine and the voltage is subdivided by a balancing set *A B* connected as shown.

77. Fig. 49 shows a method of operating motors from an Edison three-wire system that is sometimes used where high and low speed are desired, but where a large number of different speeds are not necessary. It is, in fact, a simple multivoltage system, and is very convenient for

the operation of printing presses, machine tools, etc. The armature is connected across 110 volts for low speed, and 220 volts for high speed. A certain range of intermediate speeds can be obtained by using a rheostat *F* in series with the field. *A* is the main switch, which is left closed during the time the motor is in operation. *B* is a double-throw switch; when thrown up it connects the armature across 110 volts, and when thrown down, across

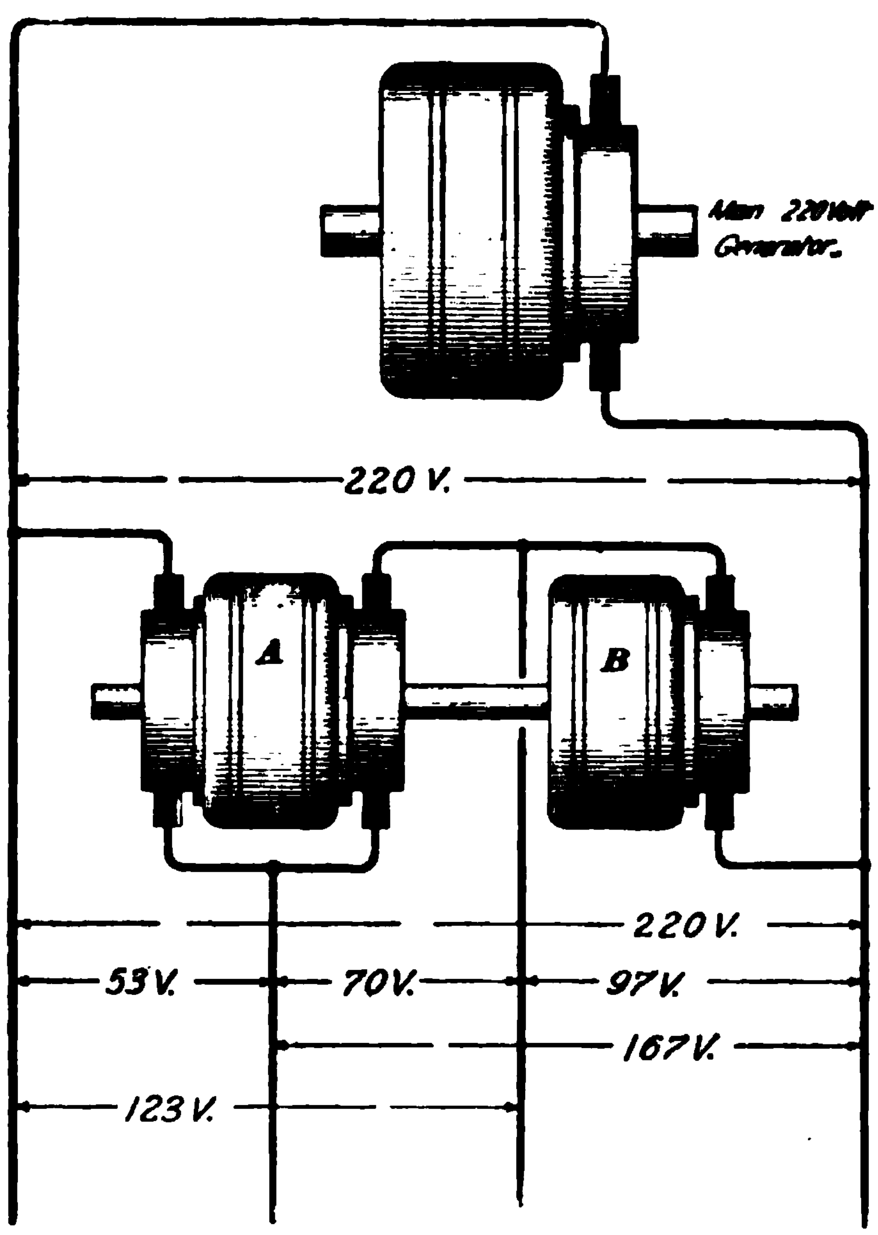


FIG. 48

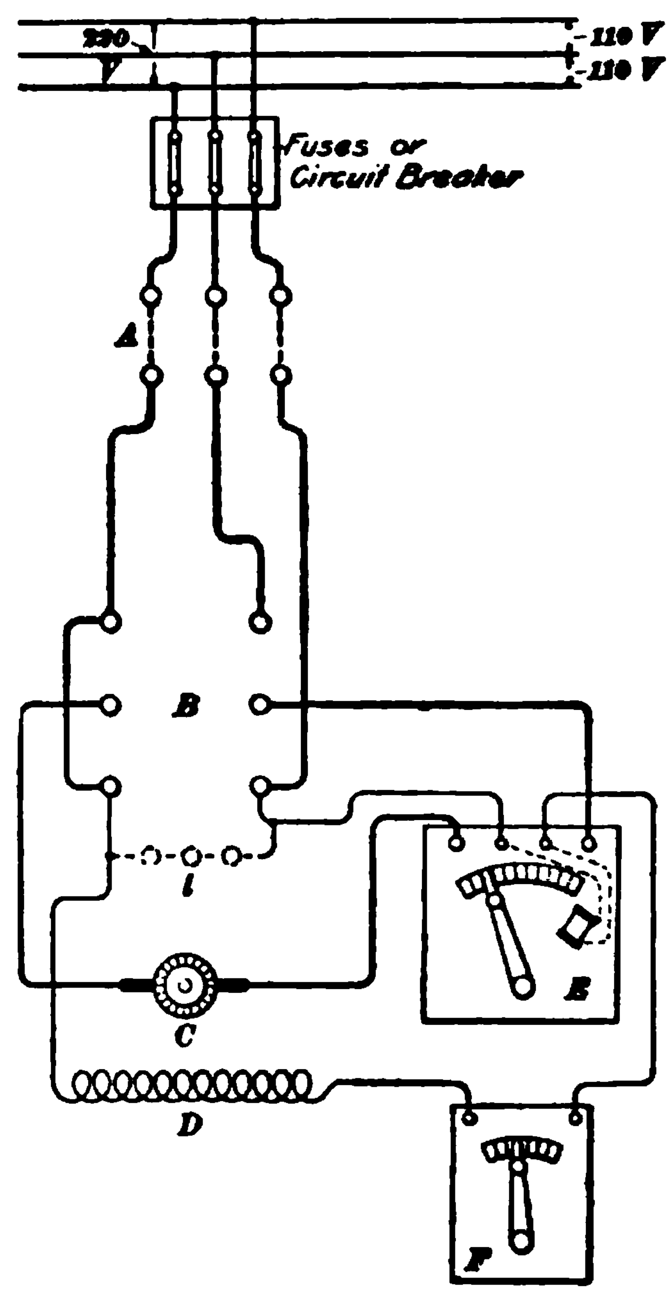


FIG. 49

220 volts. The field is excited from 220 volts as soon as switch *A* is closed, and remains excited no matter what the position of switch *B* may be; a starting rheostat *E* is placed in the armature circuit. It will be seen that when switch *A* is opened, the field circuit is broken, and in order to avoid an inductive discharge, lamps *l* may be connected across the field. In some cases a small auxiliary switch operated by the starting-box lever is connected in series

with these lamps, so that they do not burn until the starting-box lever moves from the on-position when the circuit is opened at *A*. Sometimes an automatic release is provided on the field-regulating rheostat *F*, so as to make sure that the motor will always be started with full field strength.

With two line voltages, it is possible to obtain a speed variation of from 1 to 6 by using resistance in the field. Where this system is regularly applied, the motor is connected to a controller that inserts the field resistance and changes over the armature from one voltage to the other, so that the speed may be changed smoothly and gradually. Of course, a regular controller constructed on similar lines to a street-railway controller is preferable to the arrangement of switches and rheostats shown in Fig. 49, and is more easily operated, but Fig. 49 shows a useful plan of connections in case a regular controller is not at hand.

TEASER SYSTEM OF CONTROL

78. The so-called **booster-teaser system** of control has been developed by the Bullock Electric Manufacturing Company, its special object being the control of large printing presses. These presses have to be run very slow during the process of *making ready*, and it is necessary to have some system of control that will allow the press to be moved very slowly, perhaps only a few inches at a time, and also allow it to be run at any intermediate speed or at full speed as desired.

79. Fig. 50 will serve to illustrate the general features of this method. *A* is the motor provided with a shunt field *f* and a series-field *g*. *B* is a small dynamo, or *booster*, driven by a shunt motor *C*. *B* and *C* are mounted on the same base and are connected by a shaft. In series with *A* is a small amount of resistance *d*, and an adjustable resistance *e* is placed in series with *C*. The booster generator, in addition to its shunt field winding, not shown in the figure, is provided with a powerful series-winding *k*

that causes the generator voltage to increase as the current delivered by it increases.

Assume that the main circuit through the motor is opened at *l* and that it is desired to operate motor *A* at a very low speed and yet make it exert a powerful torque. Motor *C* is first started, using *e* as a starting resistance. The current for this motor, after passing through *C*, passes through *A* and thence to the line. The voltage *E'* generated by *B* is applied to *A*, and consequently the speed at which *A* will run and the amount of current, and hence the torque, can be adjusted by varying the voltage of *B*. Motor *A* can therefore be supplied with a large current at low voltage,

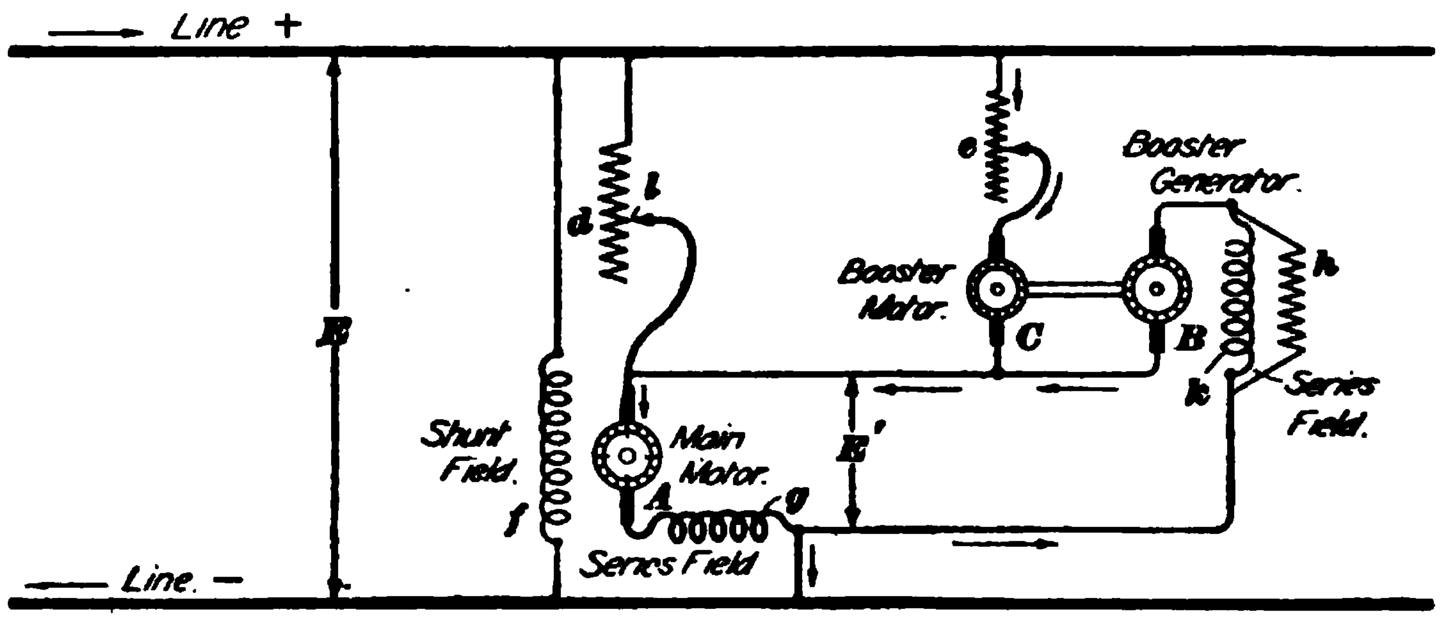


FIG. 50

thus giving a large torque at low speed, without drawing a large current from the mains, because the motor generator set *C B* transforms the high-voltage current supplied to *C* to a low-voltage current delivered by *B*. For high speeds, the teaser can be dropped and the main motor *A* supplied with current through the resistance *d* with very little loss in efficiency, since at the high speeds *d* would be either cut out altogether or the amount included in this circuit would be small. The booster generator has an adjustable shunt *h* across its series-coils, so that their effect can be varied. The regulation of the booster voltage and the various connections necessary to operate the booster in connection with the main motor, together with the cutting in and out of resistance, are effected by a drum type of controller similar in general construction to a railway controller.

CONTROL BY VARIATION OF FIELD RELUCTANCE

80. As previously stated, speed control by variation of the field exciting current is limited in range, the exact range depending on the design of the motor, and with ordinary motors, not exceeding 25 to 33 per cent. Motors are built in which the field strength is varied by leaving the exciting current constant and varying the reluctance of the magnetic circuit to obtain different degrees of field strength. This method, as originated by Mr. F. A. Johnson, is used in the Stow motors, and by means of it a speed variation of 125 per cent. can be obtained.* At first glance

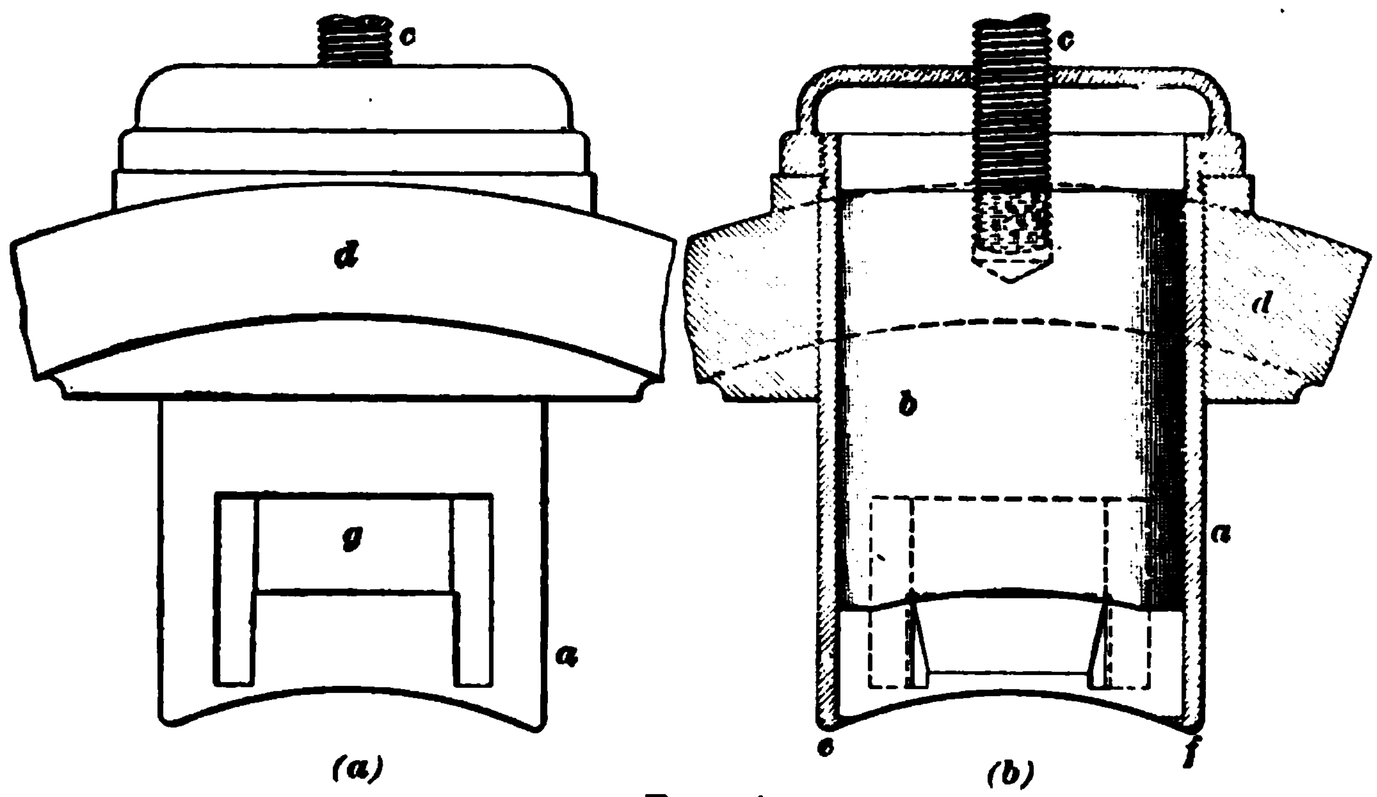


FIG. 51

it would appear that a variation in field strength by variation of the reluctance would have no advantage over a variation by a change in the exciting current. The objection to the latter is that a considerable weakening of the field by cutting down the exciting current interferes with the commutation, whereas by the former method the field can be greatly weakened and a suitable commutating fringe maintained so that the motor will operate without sparking.

Fig. 51 shows the peculiar style of pole piece used on the Stow multipolar motors; * (*a*) shows the external appearance

---

* G. Frederick Packard, Transactions American Institute Electrical Engineers, November, 1902.

and (*b*) a vertical section. The pole piece consists of two parts—an outer shell *a* and a movable core or plunger *b* that can be moved up or down by means of the screw *c*; *d* is the yoke of the magnet frame, and it is evident that when *b* is at its lowest position, the pole piece offers the minimum reluctance to the magnetic flux, because the pole piece is then practically solid. The speed will therefore be a minimum in this position of the core. As the plunger is drawn up, the flux is compelled to reach the armature by way of the thin shell *a*, which has a high reluctance and therefore cuts down the flux. Openings are cut in the shell, as shown at *g*, and when the core is drawn up, practically the whole flux has to pass into the armature by way of the pole tips *e*, *f*, thus providing a good commutating fringe and preventing sparking. As the core is drawn up, it is evident also that there is considerable reluctance placed in the magnetic path through which the cross-magnetizing turns act, and this also tends to secure sparkless operation. In the multipolar motors all the cores are connected by suitable gearing, so that they can be moved together. This special method of field control gives a much wider variation than the ordinary method, but it makes the construction of the motor somewhat expensive.

DESIGN OF DIRECT-CURRENT MOTORS

81. Since direct-current motors are constructed in the same way as direct-current dynamos, and the same requirements for high efficiency apply to both, it follows that the machine that makes a good dynamo will, in general, operate well as a motor. On the other hand, some machines that operate fairly well as motors will not operate well as dynamos. For example, some small shunt motors and series-motors will not operate when driven as dynamos, because they are not capable of exciting their fields; whereas, when they are run as motors their fields are excited by current from the mains, and they are therefore capable of operation. Also, it is possible that a machine unstable in its operation

as a shunt dynamo might operate all right as a motor, because in the latter case its fields are excited from the mains. In designing continuous-current motors, therefore, we may determine what the output of the motor would be if run at the required speed as a dynamo, and then design the motor as if it were a dynamo, making use of the various rules already given in connection with continuous-current dynamo design.

DETERMINATION OF OUTPUT

82. Suppose a given machine be run as a dynamo; the total electrical power developed in the armature will be equal to the power delivered at the terminals plus the loss due to armature resistance, and the loss in the field or the power delivered will be the total power developed in the armature multiplied by the electrical efficiency. When the machine is operated as a motor, the electrical energy developed in the armature will be the total electrical energy supplied from the mains less the loss due to field and armature resistances, or it will be the total energy supplied multiplied by the electrical efficiency of the motor. If E_m is the counter E. M. F. of the motor, I the current flowing through the armature, and E the E. M. F. between the mains, we have for a series motor

$$\text{total energy supplied from mains} = E\,I \qquad \textbf{(15)}$$

because in the case of a series motor the current in both armature and field is I. Also,

$$\text{energy developed in armature} = I\,E_m \qquad \textbf{(16)}$$

and

$$\text{electrical efficiency} = \frac{I\,E_m}{I\,E} = \frac{E_m}{E} \qquad \textbf{(17)}$$

For a shunt motor, we have

$$\text{total energy supplied} = I\,E + i\,E \qquad \textbf{(18)}$$

where i is the current in the shunt field, and

$$\text{energy developed} = I E_m$$

$$\text{electrical efficiency} = \frac{I E_m}{E(I+i)} \qquad (19)$$

In the case of a dynamo, the total electrical energy developed in the armature is less than the total energy supplied at the pulley by the amount of the losses due to friction, hysteresis, and eddy currents. In a motor the useful output at the pulley is equal to the total electrical energy in the armature less the above losses, or is the total electrical energy generated multiplied by the efficiency of conversion of the motor.

83. From the foregoing, it will be seen that if we know approximately the values of these efficiencies for the size of motor that we wish to design, we can calculate what the output of the motor would be if run as a dynamo, and then

FIG. 52

proceed to design it as if it were a dynamo. Fig. 52 shows the approximate values of these efficiencies for motors up to 150 horsepower. The upper curve A gives the electrical

efficiency at full load, that is, the ratio of electrical energy developed in motor armature to input, and the lower curve B gives the efficiency of conversion or the ratio of power developed at pulley to electrical energy developed in armature.

DESIGN OF 10-HORSEPOWER SHUNT MOTOR

84. We will suppose, for example, that it is desired to design a 10-horsepower shunt motor to operate on a 220-volt circuit and run at a speed of 1,000 revolutions per minute at full load. The field takes 3 per cent. of the total electrical input. It is required to find the current capacity of the armature of the corresponding dynamo, and also the voltage that it must generate when run at the above speed, so that we may proceed to design the motor as if it were a dynamo. The efficiency of conversion of a machine of this size is, according to Fig. 52, about .88, and the electrical efficiency is about .89. In order, then, to get a useful output of 10 horsepower, the input must be $\frac{10 \times 746}{.88 \times .89} = 9{,}525$ watts. The line pressure is 220 volts; hence, the total current taken at full load is $\frac{9{,}525}{220} = 43.3$ amperes, nearly. Of this current input 3 per cent., or about 1.3 amperes, flows around the field, so that the armature current at full load would be about 42 amperes. The total electrical energy in the armature is $\frac{10 \times 746}{.88} = 8{,}477$ watts; hence, the voltage generated in the armature must be $\frac{8{,}477}{42} = 201.8$ volts. In order, therefore, to obtain a motor that will deliver 10 horsepower, we must design a dynamo of which the armature has a current-carrying capacity of 42 amperes and that will generate 202 volts, nearly, when run at a speed of 1,000 revolutions per minute. When this machine is run as a motor, the speed at no load will be slightly over 1,000 revolutions per minute, because the counter E. M. F. generated will then be nearly 220 volts. The shunt field would be designed

for a current of 1.3 amperes, and the winding would be calculated in the same way as the shunt winding for a dynamo, except that no allowance would be made for a field rheostat, the winding being designed for connection directly to the 220-volt mains.

85. The output of the dynamo corresponding to a series motor is determined in much the same way as that for a shunt motor, formulas **15**, **16**, and **17** being used. Of course, in a series motor the field winding must be capable of carrying the full-load current, but the efficiency, etc. for the two types of motor of the same output should be about the same.

DESIGN OF 10-HORSEPOWER SERIES MOTOR

86. Suppose it were desired to design a 10-horsepower series motor to operate on 220-volt constant-potential mains. We will take the loss in the field as 3 per cent., as before, and calculate the current and voltage output of the corresponding dynamo accordingly. The efficiencies will be the same as before, that is, electrical efficiency = .89 and efficiency of conversion = .88. The total input will be 9,525 watts, or 43.3 amperes. In this case, however, the armature must be designed for 43.3 amperes, instead of 42, as before. The total electrical energy in the armature will be 8,477 watts, as in the last case, and the counter E. M. F. will be $\frac{8,477}{43.3}$ = 195.8. The dynamo must therefore have an armature wound to deliver 43.3 amperes at 195.8 volts. The voltage generated by the armature is less in this case than with the shunt motor, because a portion of the line E. M. F. E is used up in forcing the current through the field coil. The speed of the motor would vary with the load, since the field magnetization varies with the load.

87. It is especially important, in connection with the electrical side of motor design, to see that the field is very strong compared with the armature, in order to minimize the shifting of the brushes with the load. This is especially

necessary in the case of motors, because they are liable to run under large and sudden fluctuations in load, and in many cases are frequently reversed, thus rendering a fixed point of commutation extremely necessary.

MECHANICAL DESIGN

STATIONARY MOTORS

88. The general mechanical design of stationary motors is much the same as that of stationary dynamos; in fact, in many cases the same castings, armature disks, etc. are used for both. Both series motors and shunt motors are built in the same way, the only difference being in the field winding. The parts of a motor should be made as simple as possible, since motors do not generally get the same amount of care as dynamos. Carbon brushes are used almost exclusively, as they tend to keep down sparking with changes in the load.

89. For many classes of work it is desirable to have a motor that is partially enclosed. If the motor is in an exceptionally dusty or dirty location, it should be wholly enclosed. It must be remembered, however, that the more a motor is enclosed the less are the facilities for the dissipation of heat, and for a given allowable temperature rise, a motor fully enclosed would have a considerably smaller capacity than the same motor open.

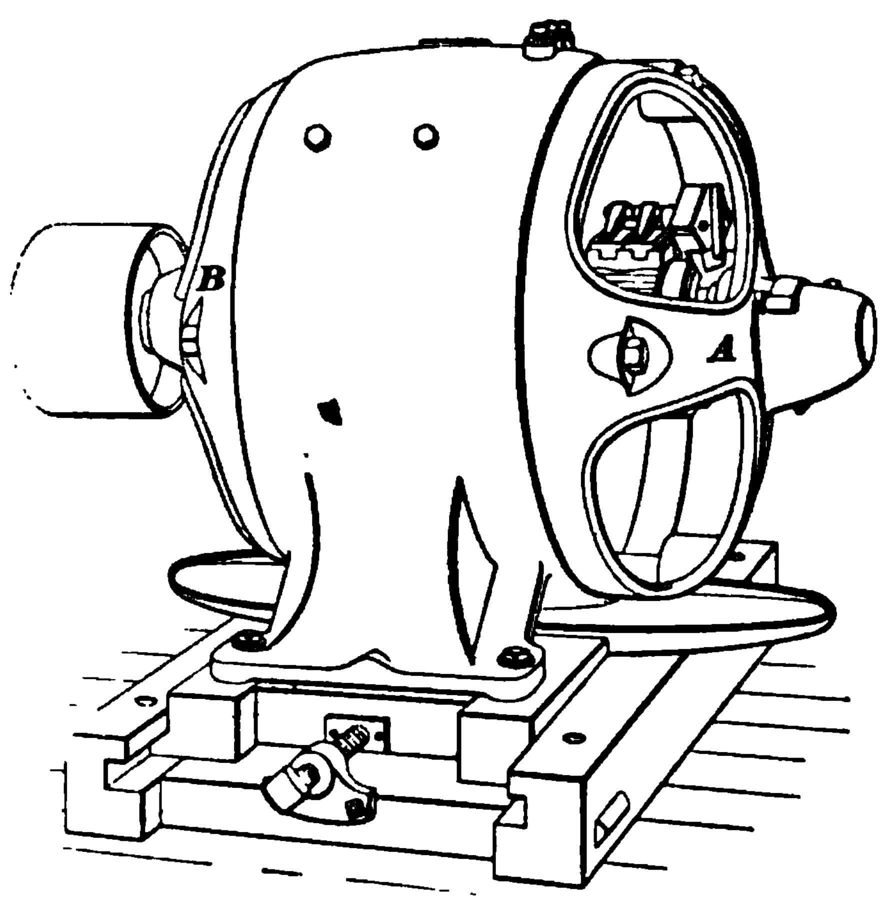


FIG. 53

Fig. 53 shows a 10-horsepower motor of the semienclosed

type made by the General Electric Company; it represents a style of construction very largely used for motors of moderate output. The bearing shields *A*, *B* are bolted to the field frame by means of four bolts, and by changing the position of the end shields, the motor can be attached to a side wall or suspended from a ceiling. If desired, the openings in the end frames can be closed by cast-iron covers, thus changing the motor into one that is wholly enclosed. It is better not to enclose a motor altogether unless it is absolutely necessary on account of dirt or flying particles. Fig. 54 shows a motor of similar type provided with back gearing in order to secure a slow speed. The end shields are provided with bearings that carry the secondary

FIG. 54

shaft, and the gears are protected by a gear-case that is partly filled with oil. In the figure, the upper half of the gear-case is removed. Motors of large size are usually constructed on the same lines as generators; in fact, the same castings are frequently used for both. It will not be necessary, therefore, to give further illustrations. Street-railway motors form a class almost by themselves and detailed descriptions of them will be found in *Electric Railways*.

CARE AND OPERATION OF DYNAMOS AND MOTORS

90. The following gives briefly some of the more important points relating to the care and operation of direct-current machines. As a rule, alternating-current machinery, described later on, does not require as close attention as direct-current, because on many alternating-current machines there is no commutator to give trouble. Space does not permit the consideration of all the troubles or faults that may arise in connection with direct-current machines, so that only the more common and important ones will here be taken up.

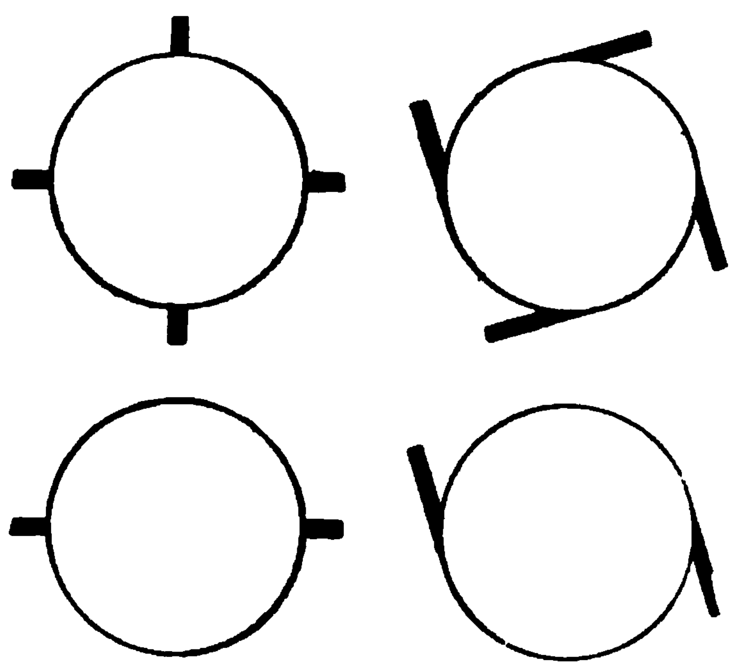
GENERAL CARE OF MACHINES

91. The dynamo or motor, and all devices connected with its operation or regulation, should be kept perfectly clean. No copper or carbon dust should be allowed to accumulate to cause breakdowns in insulation. The oil gauges and grooves should be kept in working order and the oil in the wells should be renewed at regular intervals. The brushes should be kept clean. They should be set and trimmed to fit the commutator, and if copper brushes are used, they should be taken out once in a while, whenever they become clogged, and dipped in gasoline to cleanse them. New carbon brushes should be sandpapered to fit the commutator, by sliding a piece of sandpaper back and forth between them and the commutator. Do not use emery paper for cleaning the commutator, as emery is more or less of a conductor and may cause short-circuiting between the bars; also small pieces of emery become lodged in the brushes and scratch the commutator.

Oil should be used very sparingly, if at all, on the commutator; to lubricate it, put a film of vaseline on a canvas cloth, fold the cloth once, and let the commutator get only what goes through the pores. Never allow a loose article of any kind to lie on any part of a machine.

BRUSHES

92. On direct-current machines, the brushes and commutator require, perhaps, more attention than all the other parts of the machine put together. Brushes are of two kinds: *radial* and *tangential*. **Radial brushes** point straight at the center of the commutator; their direction is parallel to the radius, as shown in Fig. 55 (*a*). **Tangential brushes,** Fig. 55 (*b*), are frequently made of copper and are found, as a rule, on lighting machines. Radial brushes are made of carbon.



(*a*) (*b*)

FIG. 55

Carbon radial brushes are always used on machines that must admit of being reversed in rotation. With carbon brushes, the commutator takes on a dark-chocolate polish and the brushes emit a squeaking noise at starting or stopping.

93. Carbon brushes are made in several grades of hardness, adapted to different conditions of working and different kinds of commutators. In stationary direct-current work, soft carbon is used; on street-car work, hard carbon.

The proper pressure for a brush depends on the material and condition of the commutator and on the material of the brush itself. A copper brush does not, as a rule, call for as much tension as a carbon brush, and soft carbon will run

with less tension than hard carbon; a rough commutator needs more brush tension than a smooth one; for given brush contact, large currents call for more pressure than small ones. Finally, where there are several brushes in each holder, the tension must be the same on all, so that they will all take about the same current. This tension should not be great enough to wear out the commutator unnecessarily or cause an unnecessary amount of friction.

If the contact between the brush and the commutator is loose, the contact resistance will be high and heating will result. On the other hand, increasing the pressure beyond a certain amount results in very little reduction of resistance, but greatly increases the friction. For stationary work, a pressure of 2 to $2\frac{1}{2}$ pounds per square inch of brush contact surface should be sufficient. For railway work, the pressure has to be much heavier on account of the jarring to which the motor is subjected.

94. One weakness of carbon brushes is that they, at times, stick in the holder so that the tension spring is not strong enough to force down the brush to its place, and even if it does force it down, the pressure on the commutator will be too light. This very serious fault may be due to either of two causes: lack of uniformity in the thickness of the brush, or an excess of paraffin in the brush. If a brush is thicker at one end than it is at the other, it may go into the holder freely if put in thin end first, and might not go in at all on the thick end. The result of this is that as soon as the brush wears down to a point where the thick end enters the holder it sticks. On the other hand, the fault may be due to a nick or burr in the brush holder itself.

The second source of trouble—an excess of paraffin in the brush—is accounted for as follows: If a carbon brush is snugly fitted into the holder so that it slides back and forth freely, but without any clearance, while the holder and brush are cold, as soon as they become warm, the paraffin, which is mixed with the carbon for lubricating purposes,

oozes out, forms a paste with whatever carbon or copper dust there may be present, and causes the brush to stick. It is very essential that the brushes should be kept clean and trimmed to fit the commutator.

THE COMMUTATOR

95. The **commutator** is the most sensitive part of a machine, and its faults are liable to develop more quickly than those of any other part. When a commutator is in the best possible condition, it becomes a dark-chocolate color, is smooth, or glazed, to the touch, and causes the brushes, if of carbon, to emit a characteristic, squeaky noise when the machine is turning slowly. Under no circumstances should any weight be allowed to rest on the commutator, nor should it be caught with a sling when the armature is being lifted. To secure the best results, the brush holders should be set as close to the commutator as possible, so as to do away with chattering.

96. If a dynamo or motor is not overloaded too much, if the brushes are set properly, and if the commutator is made of the proper material, it should seldom get rough. As a rule, sandpaper and emery cloth are used around machines much more than they should be. For ordinary roughness of the commutator, due to some temporary abnormal condition, it is well enough to use sandpaper, but for chronic roughness some more permanent treatment must be applied.

If a commutator, when it is built, is not properly baked or screwed down after it is baked, it is liable to bulge out in the course of time under the action of the heat due to its normal load and the centrifugal force, or it may develop loose bars. In the case of the bulging of one side, sandpaper will not do any good. The best thing to do with a commutator that bulges badly is to take it off, bake it so as to loosen the insulation, tighten it up well, and turn it off

in the lathe. For ordinary curvatures of surface, that is, unevenness due to wear, it is customary to set up a tool post and slide rest on the bedplate of the machine itself and turn off the commutator in position.

A narrow scratch or several of them all around the commutator means that there are particles of hard foreign matter under one or more of the brushes. A broad scratch around the bearing surface of the commutator probably means that one of the brush holders has been set too close or has become loose and slipped down to a point where it touches the bars.

97. High Bars.—A metallic click emitted twice, four times, or six times (according to the number of brush holders in use) per revolution indicates a high bar in the commutator; in such a case, the brushes will be seen to jump a little when the high bar passes under them. A high bar may be due either to a loose bar working out or to the fact that one bar is much harder than any of its neighbors, and therefore does not wear down at the same rate. If the high bar seems to be firm under a blow from a hammer, it will be safe to take it down with a file while the armature stands still; but if the hammer test proves the bar to be floating, it is a serious matter, and nothing short of a regular repair job will give satisfaction. In testing a bar or bars with the hammer, care must be taken not to nick or dent the commutator, as such a defacement will cause the high-bar click to be emitted and it will be misleading.

98. Low Bars.—A fault very much akin to a high bar is the low bar, which gives forth very much the same sound, but the brushes drop, instead of rising, as the fault passes under them. The low-bar trouble may be due to any of several causes: it may be due to the commutator having received a severe blow in the course of handling; to one or more bars being of poorer material than the rest; or it may be due to the gradual eating away of the bar on account of sparking at that particular place. A high bar can be

removed by filing down or turning down that bar alone to the level of the others, but to get rid of a low bar, the rest of the commutator must be turned down to its level.

99. Of course, the most serious condition is to have a commutator that is poorly made and of poor material. If the mica and copper used are not of the proper relative hardness, one will wear down faster than the other, leaving the surface of the commutator a succession of ribs. If the mica is too soft, it will pit out between the bars, leaving a trough to fill up with carbon dust and in a degree short-circuit the neighboring armature coils. If the mica bodies are too hard or too thick, the bars will wear in ruts and call for frequent turning down. The brushes should be set so that, with a slight end play of the armature, the whole commutator surface will be utilized.

THE ARMATURE

100. Armatures should be handled with great care, as it is an easy matter to bruise a coil or a lead, and this may not be noticed until the machine is started up. All armatures should be supported by their shafts as much as possible. When lying on the floor, they should lie on padding of some sort. Extra armatures not in use should be kept housed in a dry place.

101. Heating of Armatures.—An armature should run without excessive heating; if it heats so as to give off an odor, any of several things may be the matter. It may be damp—a condition that, as a rule, is shown by steaming, but which can be better determined by measuring the insulation to the shaft with a voltmeter. If low insulation is indicated, the armature should be baked, either in an oven or by means of a current passed through it in series with a lamp bank or water resistance. The baking current should not exceed the full-load current of the machine.

In applying the current to the armature, be sure that the series-field, if the machine has one, is not included in the circuit, and that the shunt field is broken; for if either field is on, the machine may start up as a motor.

102. If, instead of the whole armature running hot, the heat is confined to one or two coils, the indications are that there is a short circuit either in a coil or between the two commutator bars to which the ends of the coil connect. Such a short-circuited coil run in a fully excited field will soon burn out. A short circuit of this kind can be readily detected by holding an iron nail or a pocket knife up to the head of the armature while it is running in a field; any existing short circuits in the coils or commutator will cause the piece of metal to vibrate very perceptibly. One or more coil connections reversed on one side of the armature will, on a dynamo, cause a local current to flow from the strong half to the weaker half, and thereby cause all the coils to heat more than they should. On a motor, the effect is to decrease its counter E. M. F. so that it will take more current under given conditions, while the side containing the reversed coils will be hotter than the other side. A test for locating reversed coils will be described later.

103. One very peculiar fault to which armatures are liable is known as a **flying cross.** This is due to a loose wire that only gives trouble when the armature is in motion. The loose wire may either be broken, it may have a loose connection, or it may have defective insulation that allows it to come in contact with other wires as soon as the armature comes up to speed. In any case, the fault gives no trouble as long as the armature is at rest, but as soon as it gets up to speed, the centrifugal force throws the loose wire out of place and causes the brushes to flash.

104. Overloaded Armatures.—One of the most common causes of general trouble and heating in an armature is **overload**; this may be due to ignorance or neglect or to an

error in the instrument that measures the load. There is a great tendency on the part of owners to gradually increase the load on a machine until it may be doing about twice the work it is intended to do. If the machine is a dynamo, lamps are added to its load one or two at a time; in this way it is an easy matter to overload a dynamo without intending to. If the machine is a motor, small devices may be put on it, one at a time, until an overload is the result. Where machines are running together in multiple, one may be taking more than its share of the load, due to poor equalization. Ammeters sometimes get out of order, read incorrectly, or stick.

FIELD-COIL DEFECTS

105. Fields, like armatures, are subject to defects of various kinds; they are liable to open circuits, short circuits, and grounds. In the case of a series dynamo, an open circuit in the field will render it totally incapable of operating either as a motor or a dynamo, but no harm can come to the machine itself, unless the fault should take place while the current was on, in which case it would be apt to burn a hole in whatever happened to be around the break.

106. On a shunt machine, the amount of trouble caused by the opening of a field coil depends on whether the machine is a motor or a dynamo; and if a dynamo, on whether it runs alone or in multiple with other dynamos. If the machine is an isolated dynamo, a break in the field coil can do no further damage than to prevent the machine from generating. If, however, the dynamo is in multiple with other dynamos on the same load, the result of such a fault will be that the other machines will send a large rush of current back through the faulty machine and cause, practically, a short circuit. Breaking the field of a shunt motor destroys its counter E. M. F., so that there is no opposition to the line E. M. F. and there is practically a short circuit through the armature

107. On a compound-wound motor connected accumulatively, as soon as the shunt field breaks, the series-coils opposed to it bring the motor to a stop and start it up in the opposite direction. A compound-wound motor will, if the starting current is large enough, start up on the field provided by the series-turns.

108. The effect of the reversal of a single field coil on a machine depends on how many field coils the machine has; in other words, the more poles a machine has, the less will be the effect of an irregularity in one of them. If the machine has only two coils and one of them is incorrectly connected, the machine will not start as a motor and it will not generate as a dynamo. If there are four field coils, it will take a heavy current to start it as a motor, and the brushes will spark even while the motor is starting.

109. Short Circuits in Field.—The action of a short circuit in a field coil depends on the kind of machine and the manner in which the field coils are connected. Consider a shunt dynamo with four field coils; if the coils are in series, so that the voltage across each coil is only one-fourth of the total voltage, a short circuit in a single coil will cause it to run comparatively cool, while the remaining coils will get unusually warm. The cutting out of a single coil in four will reduce the resistance of the field circuit so that more current will flow through the remaining coils.

110. Moisture in Field Coils.—Moisture in field coils will cause them to heat. Before putting such fields into actual service, they should be baked out, either with the current or in an oven. The best way to locate a short-circuited field is to measure the resistance of the field suspected and compare it with that of a standard field of the same kind. A short-circuited shunt field can be located by short-circuiting or cutting out one field coil at a time and measuring the open-circuit voltage of the dynamo.

REASONS FOR A DYNAMO FAILING TO GENERATE

111. Loss of Residual Magnetism.—Among the many causes that may make a dynamo fail to generate, loss of residual magnetism is often one of the most troublesome. As a rule, dynamos leaving the factory retain enough residual magnetism to start on, but there are several ways in which they can lose it. Some dynamos never lose their residual magnetism, or **charge,** as it is called, while others seem to have a weakness for doing so.

112. Where a dynamo has lost its charge, the pole pieces will have little or no attraction for a piece of soft iron. Series dynamos seldom lose their charge so entirely that they will fail to pick up a field on short circuit. Where a compound-wound dynamo refuses to pick up a field with its shunt field, it can often be made to pick up by disconnecting the shunt coils and short-circuiting the machine through a small fuse. Machines can in some cases be made to pick up a field by simply short-circuiting the armature by holding a piece of copper wire across the brushes or by rocking the brushes back from their neutral position.

If none of these expedients produce the desired result, the fields must be recharged from an outside source. If the dynamo runs in multiple with other dynamos, this is an easy matter; it is only necessary to lift the brushes or disconnect one of the brush-holder cables on the dead machine and throw in the main-line switch, the same as if the machine were going into service with the others. The fields will then take a charge from the line and their polarity will be correct. If the dynamo does not run in multiple with another and there is a dynamo within wiring distance, disconnect the shunt field of the dead dynamo and connect it to the live circuit. If there are absolutely no other means available for charging, several cells of ordinary battery may be used. As a last resource, when all other available sources fail, connect the fields so as to obtain the

least possible resistance, put them in series with the armature through a small fuse, and speed the armature considerably above the normal rate. Very often a dynamo, instead of losing its residual magnetism, will acquire one of a reversed polarity, due, perhaps, to the same causes exercised to a greater degree.

113. Wrong Connection of Field or Armature. Every dynamo requires that a certain relation exist between the connection of its field and armature and its direction of rotation, or it will refuse to generate. Suppose a dynamo to be generating; if its field or armature connection (either, but not both) be reversed, it will be unable to generate; or if all the connections be left intact and the direction of rotation reversed, the machine will be rendered inert. Not only is it unable to generate with the wrong connections or rotation, but a short run under this condition will render the machine unable to generate after the conditions are corrected, unless the field is recharged, because the effect is to destroy its residual magnetism. If, then, a dynamo fails to generate, and all other conditions are apparently correct, reverse the field terminals, and see if the machine will pick up.

A shunt, or compound-wound, dynamo will not pick up if the shunt field circuit is open; the open circuit may be in the field itself, in the field rheostat, or in some of the wires or connections in the circuit. A careful inspection will generally disclose any fault that may exist in a wire or connection. To find out if the rheostat is at fault, short-circuit it with a piece of copper wire; if the dynamo generates with the rheostat cut out, the fault is in the rheostat. To find out if the open circuit is in a field coil, use a test-lamp circuit or a magneto-bell to test the coils one at a time. Before doing so, be certain that all communication is cut off between the machine under test and the line, if there are other machines on the same circuit. A field circuit is sometimes held open by a defective field switch that, to all appearances, is all right; repeated burning will oxidize the

tip of the blade and make a non-conducting blister on it; the blister will not carry current and it will press the jaws of the switch apart so that only the blister touches, and so opens the circuit. Another trivial but common cause of open circuits is the blowing of fuses.

An open circuit in the armature will interfere with the proper generation of the current, but such a fault, as a rule, announces its own occurrence in a very emphatic manner and does not, therefore, require to be looked for.

Before attributing the failure of a dynamo to generate to any of the foregoing open-circuit causes, see that the brushes are on the commutator, the field switch closed, and the greater part of the field rheostat cut out.

Always bear in mind that the E. M. F. generated when a machine is started up is very small, because the residual magnetism is weak. It may not require a complete open circuit in the field to prevent the machine picking up. A bad contact that might not interfere with the working of the machine when it is up to full voltage might be sufficient to prevent its picking up when started. A loose shunt wire in a binding post, or a dirty commutator, will introduce sufficient resistance to prevent the machine from operating. Trouble is very often experienced in making machines with carbon brushes pick up, especially if the brushes or commutator are at all greasy. If such is the case, thoroughly clean off the commutator, wipe off the ends of the brushes with benzine, and see that they make a good contact with the commutator surface.

114. Short Circuits.—A short circuit on the line will make a shunt dynamo drop its field. With a short circuit on the line, a shunt dynamo will not, therefore, pick up its field. With a series-wound or compound-wound dynamo, a short circuit on the line increases its ability to generate, because the fault is in series with the series-coils and a large current passes through them. A series dynamo, like a shunt dynamo, will not pick up if the field is short-circuited. A compound-wound dynamo will not pick up on open circuit

if the shunt field is short-circuited; it will pick up with an open circuit in the main circuit, but will not hold its voltage under load if the series-coils are short-circuited. In some cases a shunt dynamo will not pick up on full load, as this realizes too nearly the condition of a short circuit; so that to be on the safe side, it is best to let the machine build up its field before closing the line switch.

Short circuits within the dynamo itself generally give rise to indications that point out the location and nature of the fault. In any event, the first thing to find out is whether the fault is in the dynamo or out on the line; if it picks up its field when the line switch is opened, but fails to do so with it closed, the trouble is outside of the dynamo.

115. Field Coils Opposed.—Failure to generate may be due to one or more field coils being incorrectly put on, or connected, so that they oppose each other. On a compound-wound dynamo, the reversal of a shunt-field coil will generally keep the dynamo from picking up on open circuit, unless the dynamo has more than four coils; the more coils it has, the less effect has the reversal of a single coil. The reversal of a series-coil is not felt until an attempt is made to load the machine; the voltage will not come up to where it should for a given load, and the brushes are apt to spark on account of the weakening of the field.

116. Low Speed.—No dynamo will pick up its field below a certain speed, but with the field once established, the machine will hold it at a much lower speed than that required to establish it. The speed at which a series-dynamo will pick up depends on the resistance of the external circuit.

117. Among the causes of failure to generate not included in the foregoing are faults in the iron circuit, loose or open joints in the frame proper or between the pole pieces and the frame, and brushes not placed at the neutral position. Such imperfections also lower the maximum voltage of the dynamo.

FAILURE OF MOTOR TO START

118. When a motor fails to start when the controlling switch is closed, any one of several things may be the matter. There may be an open circuit, a short circuit, a wrong connection, the power may be off the line, or the trouble may be purely mechanical. If the failure to start is due to an open circuit or to absence of power on the line, there will be no flash when the switch is closed and opened again. To tell if there is any power on the line, test with incandescent lamps or a voltmeter. If the fault is an open circuit, it may be found in any of the following places: Defective switch; broken wire or connection in the starting box; loose or open connection in some of the wiring; a piece of foreign matter under one brush; brush stuck in the holder or no brush in it at all; brush springs up; fuse blown; some wire, apparently all right, broken inside the insulation; or an open circuit in some part of the motor itself. If the trouble is due to a short circuit, there will be a flash when the starting box is thrown off.

119. Among the more common sources of short circuit are: short-circuited armature coils; short-circuited commutator; short-circuited field coils; field on a shunt or compound-wound motor connected so that the armature cuts out the field winding; brushes in the wrong position. If the armature coils or commutator are short-circuited, the machine may start and turn over part way and stop again. With a field coil short-circuited, the armature will start only under a heavy current, with accompanying sparking, and will acquire a high rate of speed.

120. Wrong Connections of Shunt Field.—As previously pointed out, it is an easy matter to confuse the connections of a shunt motor so that the shunt field will not be excited at starting or at least have a very small excitation, because of its being connected across the brushes. If

such a mistake is made, the motor will fail to start unless an excessive current is made to flow through the armature by cutting out the greater part of the starting rheostat, and even then the motor may not start unless the load is light.

SPARKING

121. Sparking at the brushes may be due to any of the following causes: *Too much load; brushes improperly set; commutator rough or eccentric; high or low bars; brushes making poor contact; dirty brushes or commutator; too high speed; sprung armature shaft; low bearings; worn commutator; short-circuited or reversed armature coil; high-resistance brush; vibration; belt slipping; open-circuited armature; weak field; grounds.*

122. Too Much Load.—In this case the armature heats all over. The sparking may be lessened but not stopped by shifting the brushes ahead on a dynamo and back on a motor. If the machine is a motor, the speed will be low; if a dynamo, the voltage will be below the normal amount.

123. Brushes Improperly Set.—Brushes may be out of their proper position in either of two ways: they may be the right distance apart but too far one way or the other as a whole; this can, of course, be remedied by shifting the rocker-arm back and forth until the neutral point is found. The brushes may, as a whole, be central on the commutator, but too far apart or too close together. Such a fault must be remedied by adjusting the individual holders.

124. Commutator Rough or Eccentric.—A commutator will become rough either as a result of abuse or as a result of bad selection of the copper and mica of which it is made. An eccentric commutator acts like a bent shaft and may be the result of faulty workmanship or the result of a hard blow. In either case it must be turned true, but

before doing it be certain that the commutator is at fault and not the shaft.

125. High or Low Bar.—A high or low commutator bar causes a poor contact between brush and commutator. and hence gives rise to sparking.

126. Brushes Making Poor Contact.—The brush may be stuck in the holder; the temper may be out of the tension spring; the brush hammer may rest on the side of the holder and not on the brush; the brush may not fit the surface of the commutator; the holder may have shifted to the wrong angle. Tension springs should be paralleled by a conductor attached to the brush, so that the current will not flow through the springs.

127. Dirty Brushes or Commutator.—Some carbon brushes are liable to give out paraffin when hot, which, getting on the commutator, insulates it in spots. A copper brush is apt to get clogged with oil, dust, and threads of waste (waste should never be used on a commutator). Dirty commutators, as a rule, are the result of using too soft a brush.

128. Too High Speed.—A machine is apt to spark if its speed is too high, because it interferes with the commutation.

129. Sprung Armature Shaft.—A sprung armature shaft causes the commutator to wabble, giving very much the same symptoms as an eccentric commutator.

130. Low Bearings.—On some types of machine, excessive wear in the bearings throws the armature far enough out of center to distort the field and cause sparking.

131. Worn Commutator.—When a commutator wears down below a certain point, even if otherwise in good condition, it seems inclined to spark in spite of everything that can be done. It may be because the brushes then span

more bars, because the bars become thinner as they wear away, or it may be because an error in the angle of the holder increases with the distance from the commutator.

132. Short-Circuited or Reversed-Armature Coil. Either of these faults will cause a local current to flow, with the result that either a dynamo or a motor will require an unusual amount of power to run it even when unloaded. A motor will run with a jerky motion especially noticeable at low speeds, and the voltmeter connected to a dynamo will fluctuate. Such a fault may be due to a cross in the coil itself or contact between two commutator bars. In either case, unless the cross is removed, the coil will burn out.

133. High-Resistance Brush.—Up to a certain point, high resistance in a carbon brush is a good feature, but it is possible to get the resistance so high that the brush will spark on account of its inability to carry the current at the contact surface.

134. Vibration.—A shaky foundation will cause the whole machine to vibrate and will cause it to spark steadily, which fault can be remedied only by placing the machine on a firmer foundation.

135. Belt Slipping.—A slipping belt will sometimes cause intermittent sparking because it subjects the machine to unusual variations in speed.

136. Open-Circuited Armature.—By an open-circuited armature is meant a break in one of the armature wires or its connections. Excessive current may burn off one of the wires or a bruise of some kind may nick a wire so that the normal load or less burns it off. A commutator may become loose and break off one or more leads. In any case there are two very characteristic symptoms of an open-circuited armature: a ball of fire runs around the commutator and the mica is eaten from between the bars to which

the faulty coil is connected, the bars themselves become dark, pitted, and burned on the edges. Sometimes, on account of abuse, the armature throws solder and all the commutator connections become impaired. In such a case there are no actual open circuits, but there are poor contacts that result in making the commutator rough and black.

137. Weak Field.—A weak field may be due to a loose joint in the iron circuit, to a short circuit in the field coils, to opposition of the field coils, or to the fact that heat has carbonized the insulation so that the current short-circuits through it. Any of these influences decrease the field strength, with the result that the starting power of the motor is decreased and the speed and current are increased. On a dynamo, the E. M. F. and the ability to pick up are decreased.

138. Grounds.—On an ordinary circuit, a single ground has no effect, but two grounds can so take place that the whole or any part of the field or armature may be cut out; such a pair of grounds is nothing more nor less than a short circuit, and it falls under that head.

TESTING FOR FAULTS

139. Many of the defects that are liable to arise in connection with dynamos and motors are, of course, apparent from a mere inspection of the machine. Other defects, such as short-circuited or open-circuited field coils, short-circuited or open-circuited armature coils, etc., must be located by making tests. For tests of this kind, Weston or similar instruments are most convenient if they have the proper range for the work in hand. For measuring resistances, the *drop-of-potential method* is generally most easily applied. This method consists in sending a known current

through the resistance to be measured and noting the pressure between the terminals of the resistance; in other words, noting the pressure required to force the known current through the unknown resistance. If the resistance to be measured is very low, as, for example, an armature coil, the voltmeter must be capable of reading low and a millivoltmeter (one reading to thousandths of a volt) will be best suited to the work. Of course, a good Wheatstone bridge may also be used for measuring resistances, but it is generally not as convenient to use around a station as the drop-of-potential method.

140. Testing for Open-Circuited Field Coils.—If a machine does not pick up, it may be due to the absence of residual magnetism. If any residual magnetism is present, a voltmeter connected across the brushes will give a small deflection when the machine is run up to full speed, so that this point can easily be determined before a test is made for a broken field coil. Examination of the connections between the various coils will show if they are defective or loose; quite frequently the wire in the leads from the spools becomes broken at the point where the leads leave the spool, while the insulation remains intact, so that the break does not show. This may be detected by *wiggling* the leads.

If the break is inside the winding of one of the coils, it can only be detected by testing each coil separately to see if its circuit is complete. This may be done with a Wheatstone bridge or with a few cells of battery and a galvanometer. A low-reading Weston voltmeter makes a good galvanometer for this purpose.

If the current from another dynamo can be obtained, the faulty spool may be detected by connecting the terminals of the field circuit to the terminals of the circuit of the other machine; no current will flow through if the circuit is broken, but if a voltmeter is connected across each single field coil in succession, it will show no deflection if the coil is continuous, because both poles of the voltmeter will be

connected to the same side of the dynamo circuit. If the coil has a break in it, one of its terminals will be connected to one side of the circuit and the other to the other side, so that a voltmeter connected between these terminals will show the full E. M. F. of that circuit. Consequently, when the voltmeter is connected across a spool and shows a considerable deflection, that spool has an open circuit which must be repaired before the dynamo can operate.

This method of testing is represented by the diagram, Fig. 56; *1*, *2*, *3*, and *4* represent the field coils of a dynamo, there being a break in coil *2* at *B*. The terminals *a* and *e* are connected to the + and − terminals of a *live* circuit. It will be seen that terminals *a* and *b* of coil *1* are both connected to the + side of the circuit, and as there is no current flowing through the field circuit, there is no difference of potential between *a* and *b*; therefore, a voltmeter connected to *a* and *b*, as at *V*, will show no deflection. But terminal *c* of coil *2* is connected to the − side of the circuit; so a voltmeter connected to *b* and *c*, as at V_1, will show a deflection, and, in fact, will indicate the difference of potential between *a* and *e*.

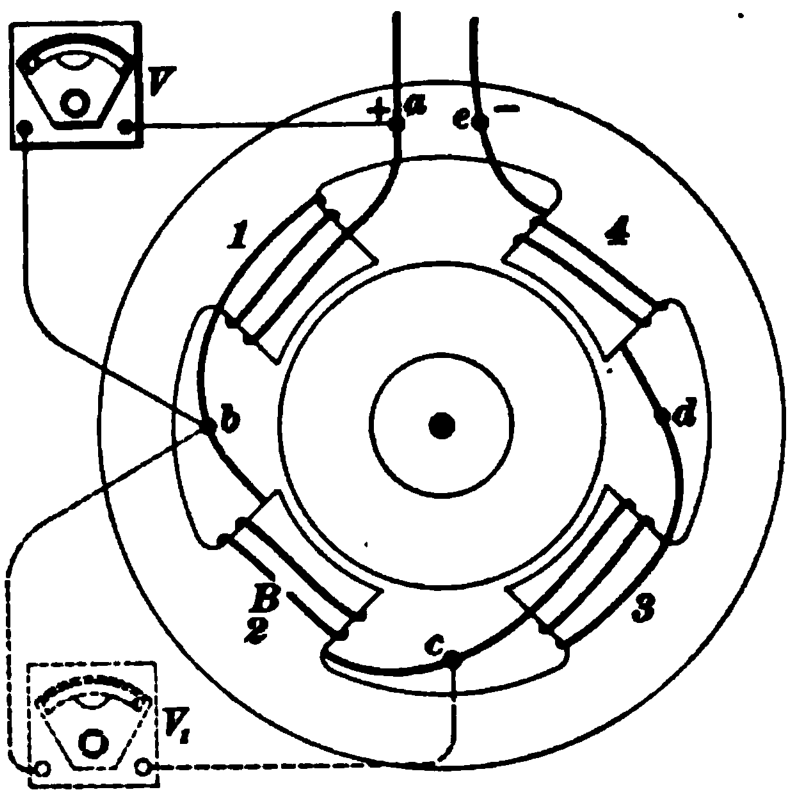


FIG. 56

141. Short-Circuited Field Coil.—It is evident that if the windings of a field coil become short-circuited either by wires coming in contact or by the insulation becoming carbonized, the defective coil will show a much lower resistance than it should. The drop of potential across the various field coils should be about the same for each coil, so that if one coil shows a much lower drop than the others, it indicates a short circuit of some kind.

142. Test for Grounds Between Winding and Frame.—After the machine has thoroughly warmed up, it should be tested for *grounds* or connections between the winding and the frame or armature core. This may best be done with a good high-resistance voltmeter, as follows: While the machine is running, connect one terminal of the voltmeter to one terminal of the dynamo, and the other terminal of the voltmeter to the frame of the machine, as represented in Fig. 57, where T and T_1 are the terminals

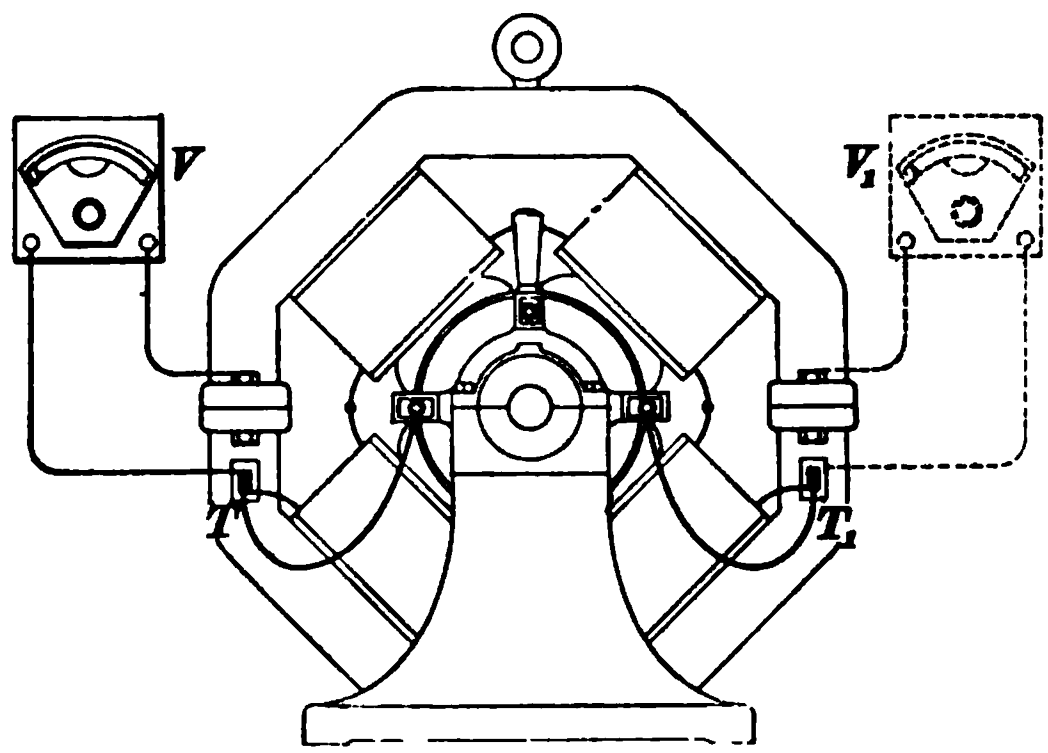


FIG. 57

of the dynamo and V and V_1 two positions of the voltmeter, connected as described above.

If in either position the voltmeter is deflected, it indicates that the field winding is grounded somewhere near the other terminal of the dynamo; that is, if the voltmeter at V shows a deflection, the machine is grounded near the terminal T_1, and vice versa. If the needle shows a deflection in both positions, but seems to vibrate or tremble, the armature or commutator is probably grounded. If in either case the deflection does not amount to more than about $\frac{1}{20}$ the total E. M. F. of the machine, the ground is not serious, but if the deflection is much more than this, the windings should be examined separately, the ground located, and, if possible, removed.

143. To locate the ground, each coil should be disconnected from its neighbor (with the machine shut down, of course) and *tested out* by connecting one terminal of another dynamo (or of a live circuit) to the frame of the machine, care being taken to make a good contact with some bright surface, such as the end of the shaft or a bolt head; the other terminal of the coil to be tested is connected to the other line through a voltmeter, as represented in Fig. 58.

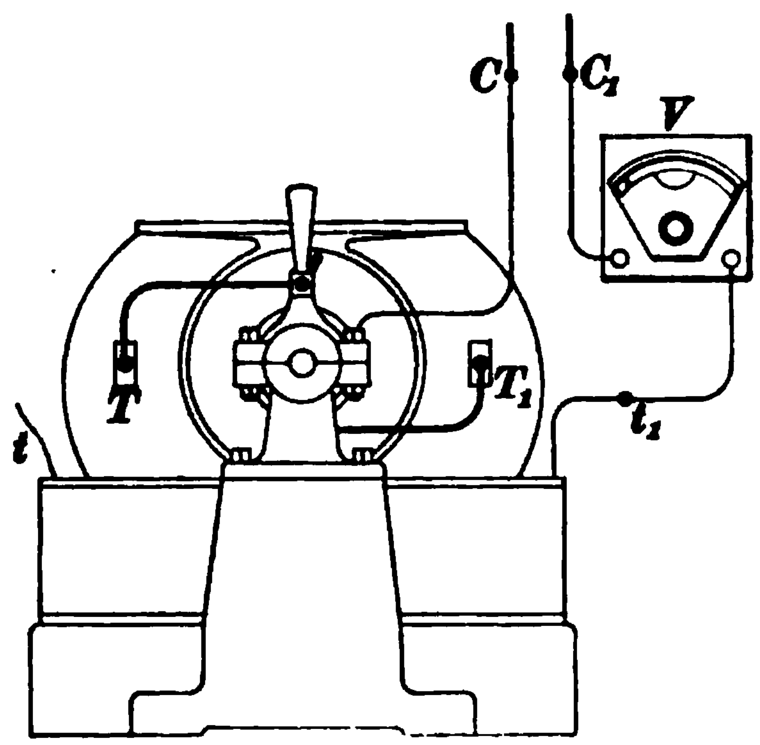


FIG. 58

Here C and C_1 represent the terminals of a live circuit, which should have a difference of potential between them about equal to the E. M. F. of the machine when it is in operation, but not greater than the capacity of the voltmeter will allow of measuring. T and T_1 represent the terminals of the dynamo, as before, and t and t_1 the terminals of the field coils, which have been disconnected from each other and from the dynamo terminals. One terminal C of the circuit is connected to the frame of the machine; the other terminal C_1 of the circuit is connected through the voltmeter V to the terminal t_1 of the field coil. If that coil is grounded, the voltmeter will show a deflection about equal to the E. M. F. of the circuit $C C_1$, but if the insulation is intact, it will show little or no deflection. The wire connecting the voltmeter with the terminal t_1 may be connected in succession to the terminal of the other coil, or coils, and to the commutator; any grounded coil of the field or armature winding will be shown by a considerable deflection of the voltmeter needle.

144. If the machine tests out clear of grounds, it should be shut down after the proper length of time and the

various parts of the machine felt over to locate any excessive heating. If accurate results are wanted, thermometers should be used, placing the bulb on the various parts (armature, field coils, etc.) and covering it with a wad of waste or rags. They should be looked at from time to time until it is seen that the mercury no longer rises, when the point to which it has risen should be noted.

145. Test for Defects in Armature (Bar-to-Bar Test).—Faults in armatures may best be located by what is known as a **bar-to-bar test.** This consists briefly in sending a current through the armature (in at one side of the commutator and out at the opposite side) and measuring the drop between adjacent bars all around the commutator. If the armature has no faults, the drop from bar to bar should be the same for all the bars. The connections for this test are shown in Fig. 59. *E* is the line from which the current for testing is obtained, and *L.B.* a lamp bank by means of which the current flowing through the armature may be adjusted. Connection is made with the commutator at two opposite points *A*, *B*. A contact piece, or crab *C*, is provided with two spring contacts that are spaced so as to rest on adjacent bars. These contacts are connected to a galvanometer, or millivoltmeter, *G*.

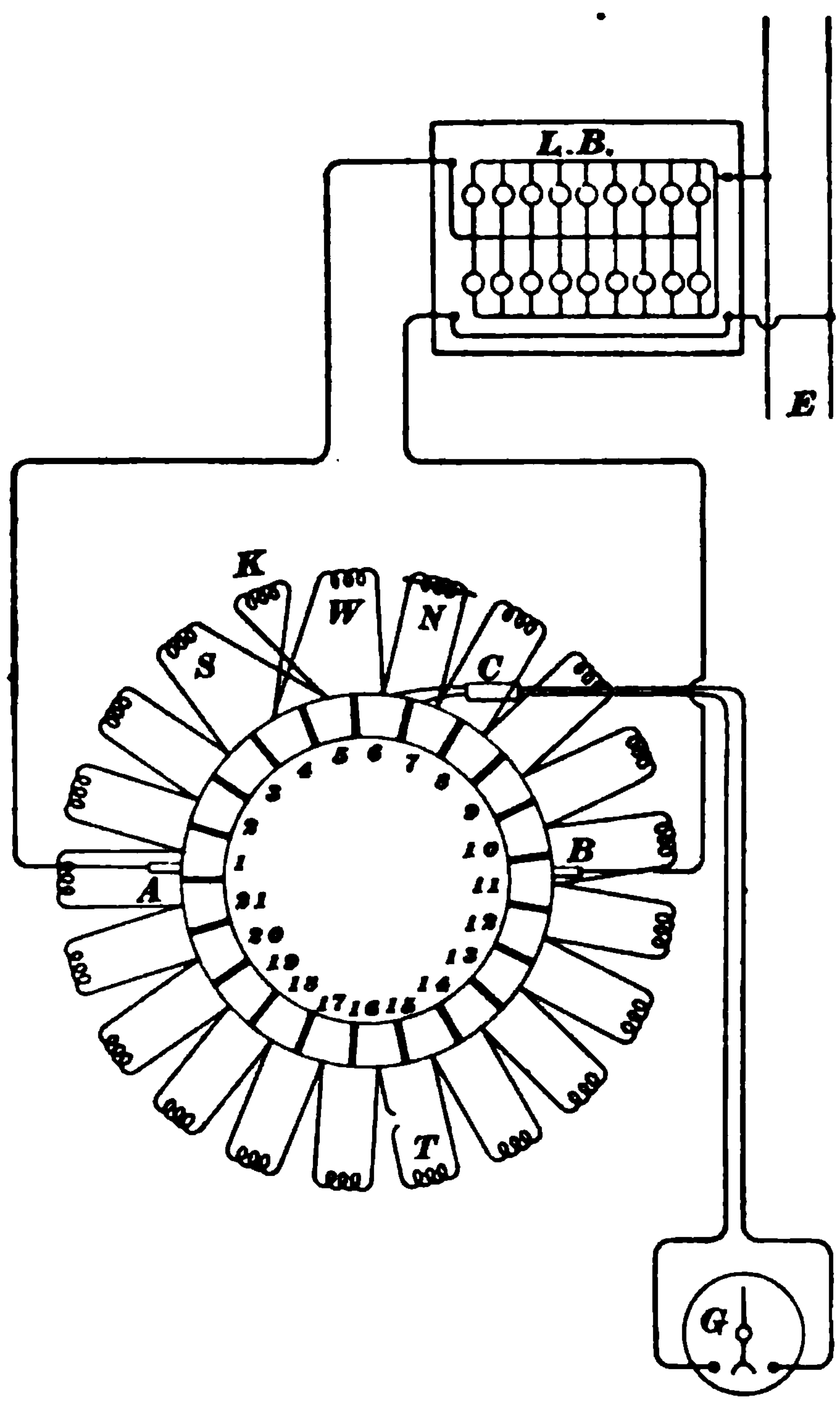


FIG. 59

For the sake of illustrating the way in which the bar-to-bar test will indicate various kinds of faults, we will suppose that in coil *N* there is a short circuit, that the commutator leads of coils *S*, *K*, and *W* have been mixed, as shown, and that there is an open circuit in coil *T*. Current will flow through the top coils from *A* to *B*, but not through the bottom coils on account of the open circuit at *T*. Terminals *A*, *B* may be clamped permanently in place by means of a wooden clamp.

146. It is evident that the deflection of the galvanometer will depend on the difference of potential between the bars. If everything is all right, practically the same deflection will be obtained all around the commutator, no matter on what pair of bars *C* may rest. The test is carried out as follows: Adjust the lamp bank until the galvanometer, or voltmeter, gives a good readable deflection when *C* is in contact with what are supposed to be good coils. The amount of current required in the main circuit will depend on the resistance of the armature under test. If the armature is of high resistance, a comparatively small current will give sufficient drop between the bars; if of low resistance, a large current will be necessary. The operator runs over several bars and gets what is called the standard deflection and then compares all the other deflections with this. In case he should start on the damaged part, he will find when he comes to the good coils a difference in deflection.

If the contact rests on bars *3*, *4*, it is easily seen that a deflection much larger (about double) than the standard will be obtained, because two coils are connected between *3* and *4* in place of only one. When on *4* and *5*, the deflection of the voltmeter, or galvanometer, would reverse, because the leads from *K*, *S*, and *W* are crossed. The deflection would not be greater than the standard, because only one coil is connected between *4* and *5*. Between *5* and *6* a large deflection will be obtained for the same reason that a large one was obtained between *3* and *4*. Between *6* and *7* little or

no deflection will be obtained, because coil *7* is here represented as being short-circuited, and hence there will be little or no drop through it. As *C* is moved around on the lower side, no deflection will be obtained until bars *15* and *16* are bridged. There will then be a violent throw of the needle, because the voltmeter will be connected to *A* and *B* through the intervening coils. When *C* moves on to *16* and *17*, there will again be no deflection, thus locating the break in coil *T*. As a temporary remedy for this, bars *15* and *16* may be connected together by a *jumper*, or piece of short wire.

147. If any of the coils have poor or loose connections with the commutator bars, the effect will be the same as if the coil had a higher resistance than it should, and hence the galvanometer deflection will be above the normal. In practice, after one has become used to this test, faults may be located easily and rápidly. It is best to have two persons, one to move *C* and the other to watch the deflections of *G*.

148. Locating Short-Circuited Armature Coils. Where there are a large number of armatures to be tested,

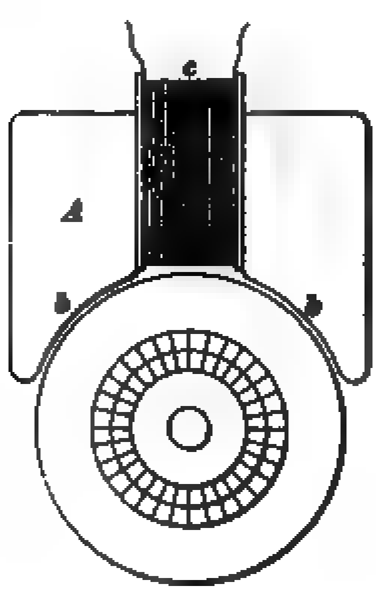


FIG. 60

as, for example, in street-railway repair shops, an arrangement similar to that shown in Fig. 60 is very convenient

for locating short-circuited coils. *A* is a laminated iron core with the polar faces *b*, *b* (in this case arranged for four-pole armatures). This core is wound with a coil *c* that is connected to a source of alternating current. The core is built up to a length *d*, about the same as the length of the armature core. The core *A* is lowered on to the armature, and when an alternating current is sent through *c*, an alternating magnetization is set up through the armature coils. This induces an E. M. F. in each coil; and if any short circuits exist, such heavy local currents are set up that the short-circuited coils soon become hot or burn out, thus indicating their location. If an armature with a short-circuited coil is revolved in its own excited field, the faulty coil promptly burns out, so that this constitutes another method of testing for such faults. To cut out a short-circuited coil, temporarily disconnect its ends from the commutator, bend back the ends out of the way, tape them so that they cannot touch each other, and put a short piece of wire, or jumper, in place of the coil so disconnected. It is always best, however, to replace the defective coil, because if the turns are short-circuited on each other, the coil may persist in heating and thus damage other coils.

ALTERNATING CURRENTS

(PART 1)

E. M. F. WAVE FORMS

1. In studying the applications of electricity, there are, in general, two distinct classes of electric currents to deal with, namely, *direct currents* and *alternating currents.* Most of the practical applications of electricity were formerly carried out by means of the direct current; but during recent years the alternating current has come extensively into use.

2. The apparatus used in connection with alternating-current installations is, in general, different from that used in connection with direct-current outfits, and must be considered separately. Moreover, on account of the nature of alternating currents, they do not flow in accordance with the simple laws that govern the flow of direct currents.

3. In continuous-current circuits, the current flows uniformly in one direction; in other words, as time elapses the value of the current does not change. This condition might be represented graphically, as shown in Fig. 1. Time is measured along the horizontal line $0a$, and as the current remains at the same value, it might be represented by the heavy line cb; the height of this line above the horizontal would indicate the value of the current, i. e., $+25$ amperes. A current of -35 amperes, which would be flowing in the

opposite direction, would be represented by the heavy line *de* below the horizontal.

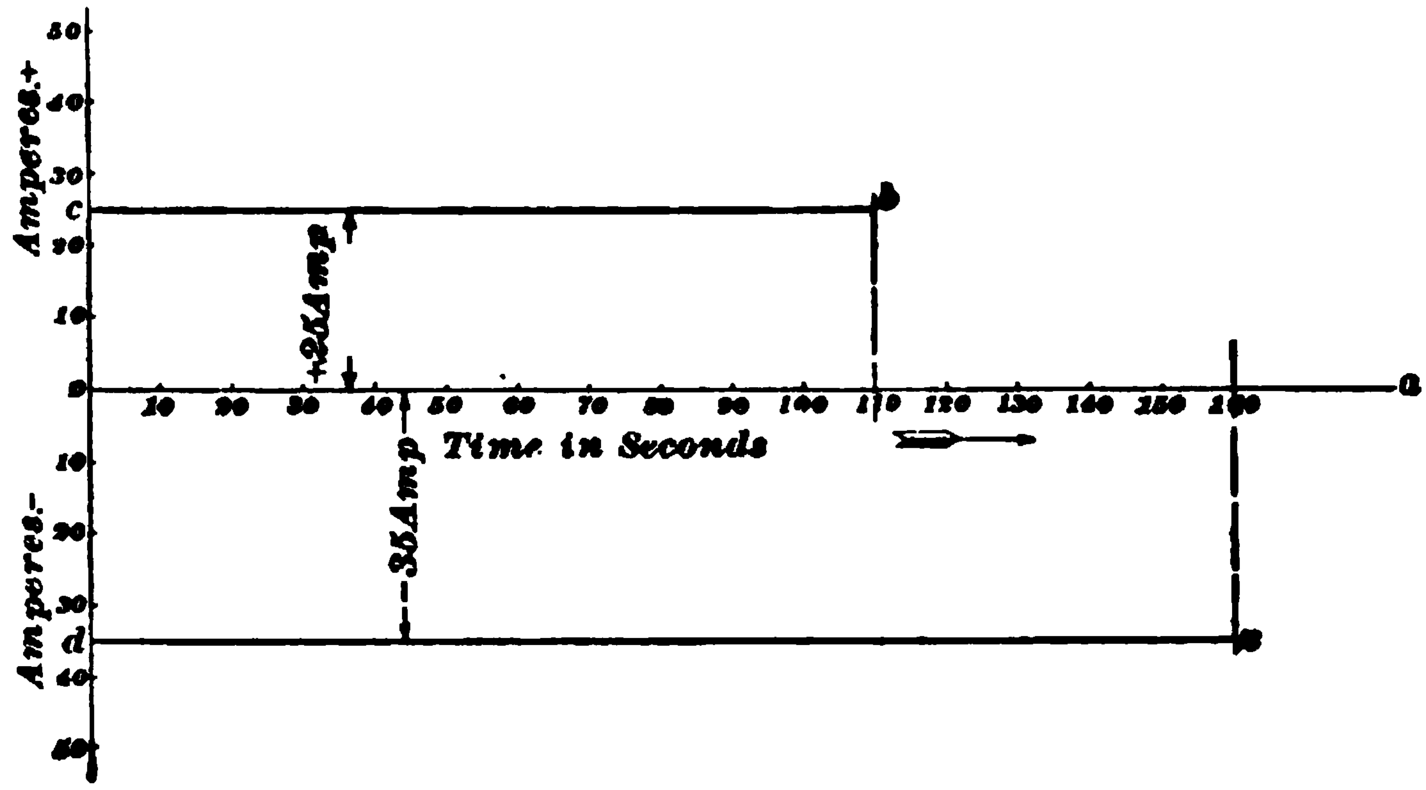


FIG. 1

4. In the case of alternating currents, the direction of the flow is continually changing. This may also be shown graphically, as in Fig. 2. In this case, a current of 25 amperes flows for an interval of 1 second in the positive direction, then reverses, flows for a similar interval in the opposite

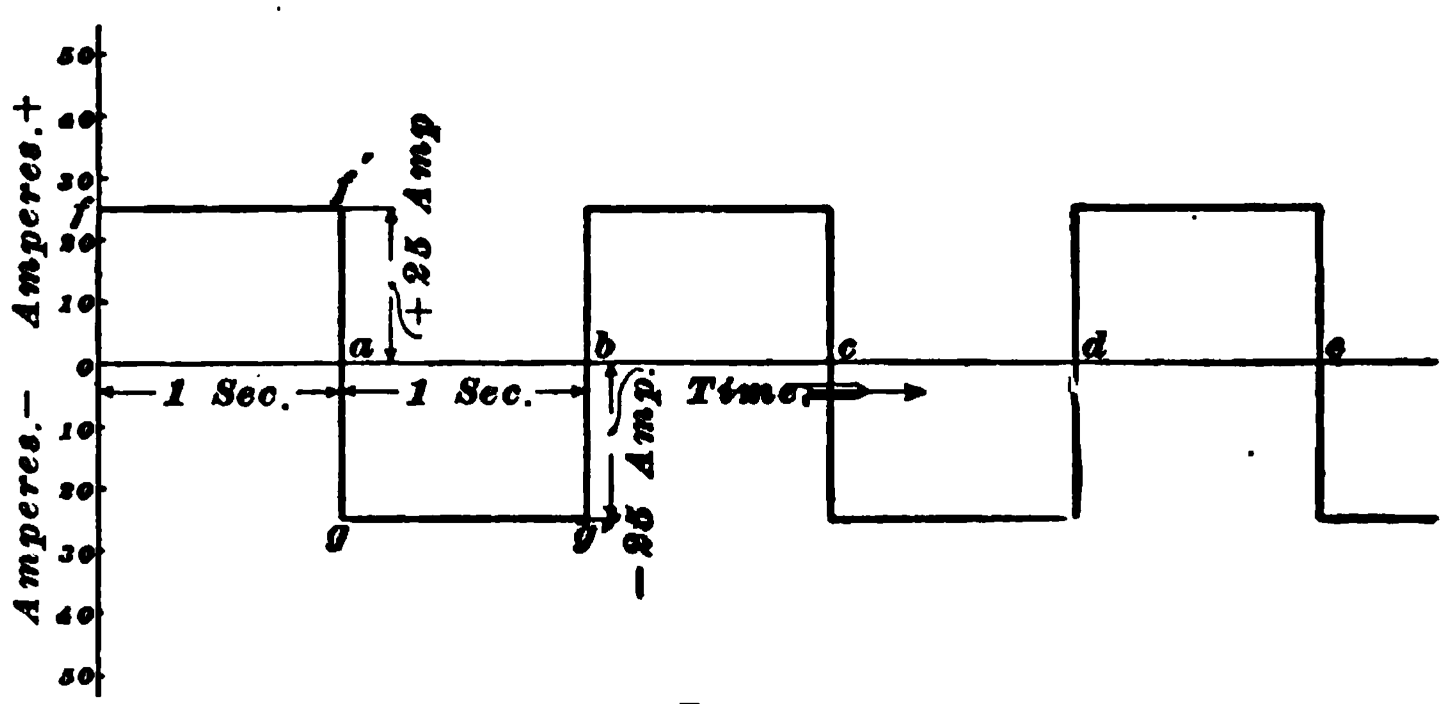


FIG 2

direction, and then reverses again. This operation is repeated at regular intervals as shown by the line, and any current that passes repeatedly through a set of values in equal intervals of time, such as that shown above, is known as an **alternating current.** The line $O f f' a g g' b$ is often

spoken of as a **current**, or **E. M. F., wave,** depending on whether the diagram is used to represent the current flowing in a circuit or the E. M. F. that is setting up the current. The positive half wave $0ff'a$ is of almost exactly the same shape as the negative half wave $agg'b$ in most practical cases. Induction coils produce E. M. F.'s that have different positive and negative half waves, but in the case of E. M. F.'s produced by alternating-current dynamos the two waves are almost identical.

5. The outline of the alternating-current waves usually met with in practice is always more or less irregular, the

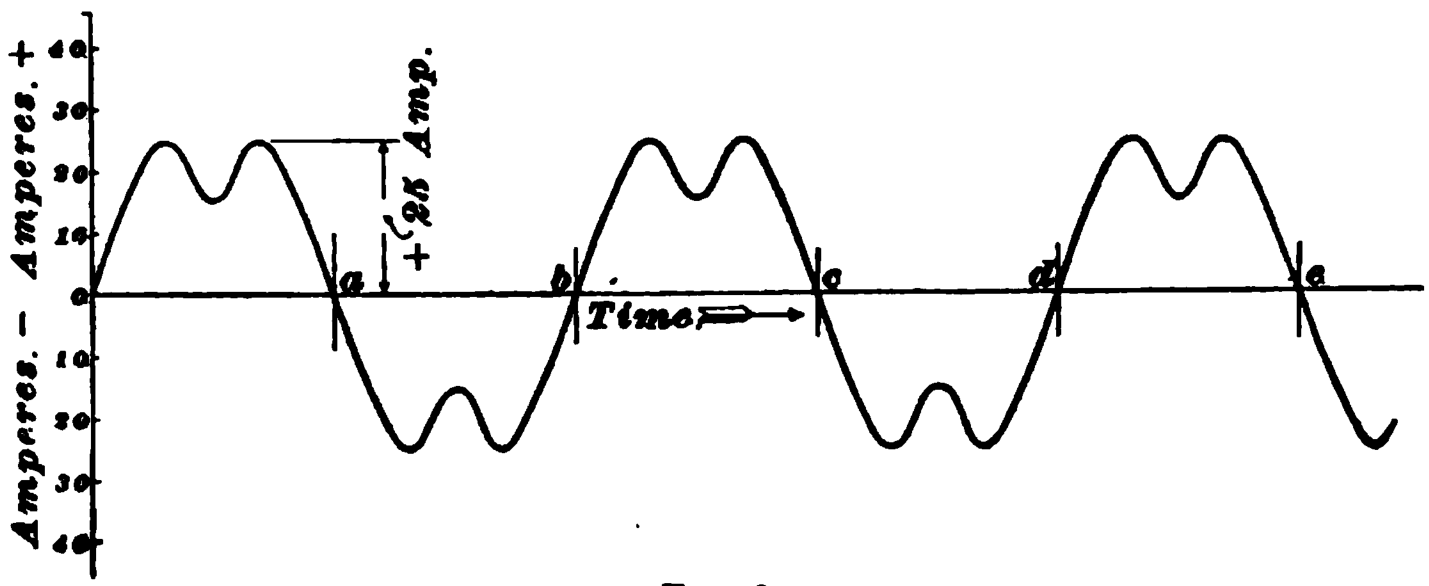


FIG. 3

shape of the wave depending largely on the construction of the alternator producing it. Some of the more common shapes met with are shown in Figs. 3, 4, 5, and 6. Figs. 3,

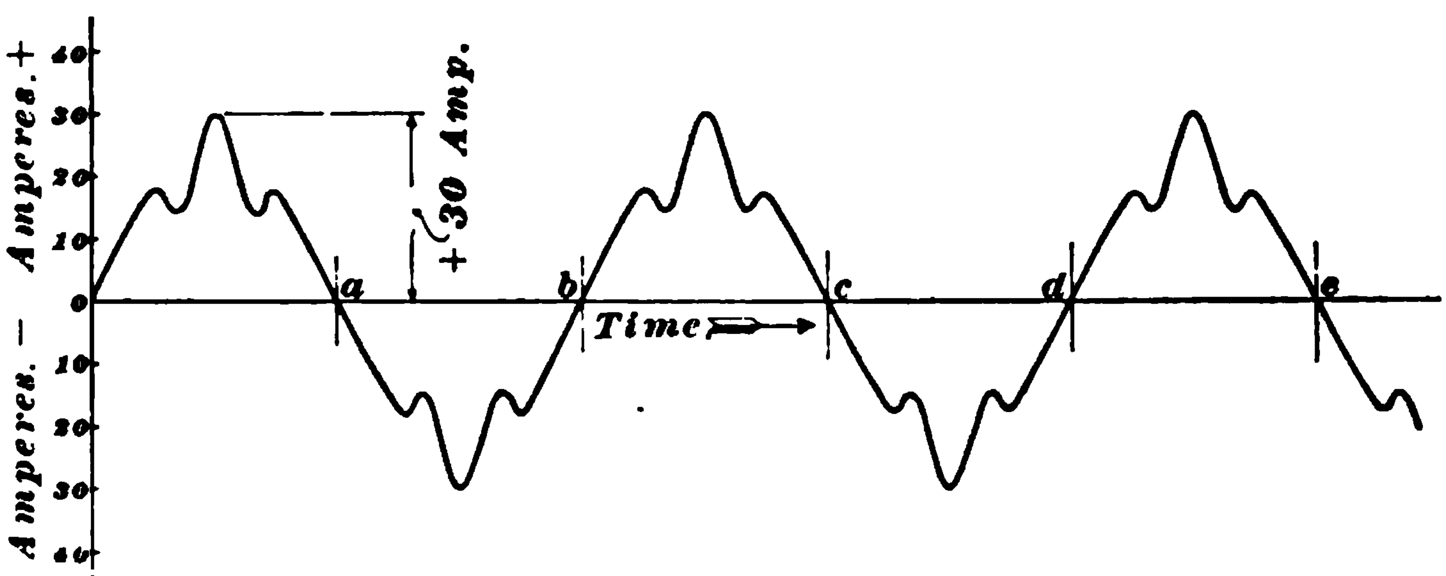


FIG. 4

4, and 5 show the general shape of the waves produced by some alternators used largely for lighting work and having toothed armatures. The student should notice that while

the waves are irregular, the same set of values are repeated over and over, and that the set of negative values of the

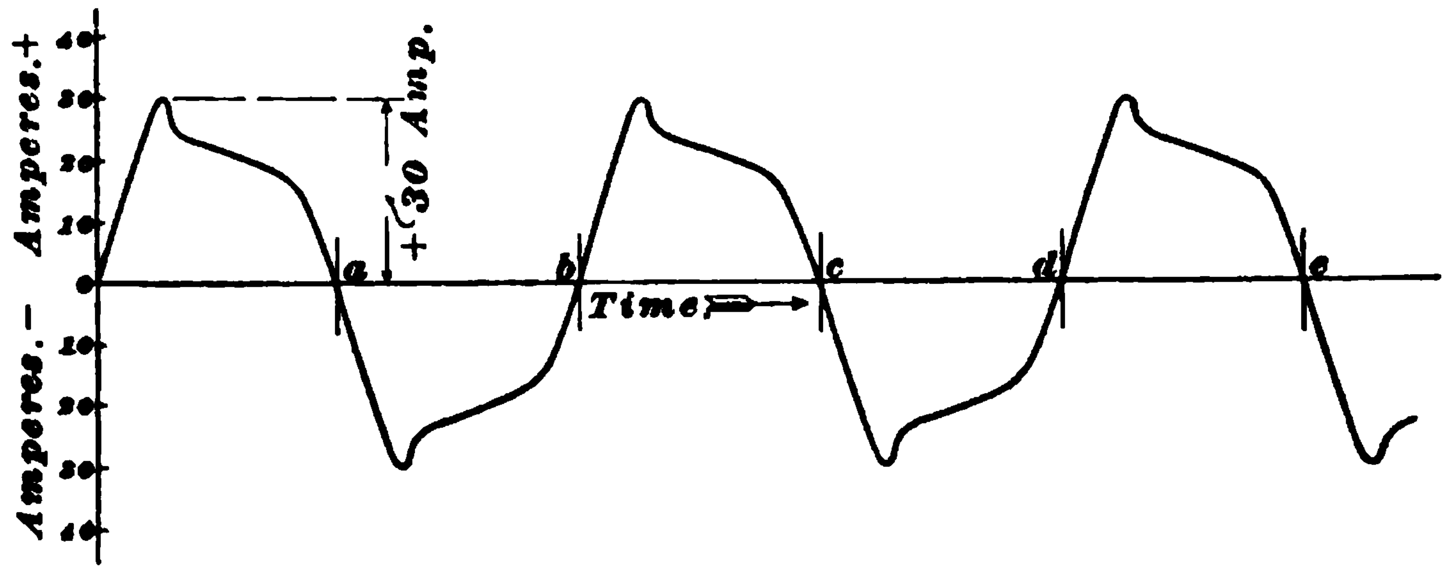


FIG. 5

current is the same as the positive, thus producing a symmetrical curve with reference to the horizontal line. Fig. 6 represents a form of wave that is commonly met with,

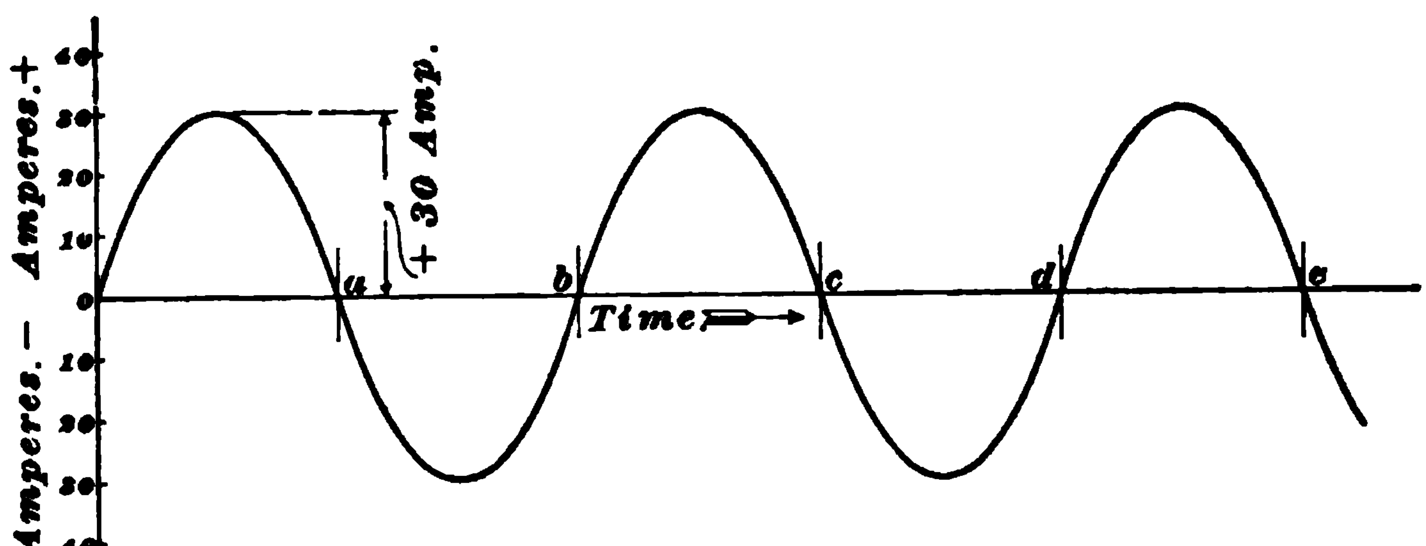


FIG. 6

especially in the case of large alternators designed for power transmission. It will be noticed that this curve is practically symmetrical as regards both the horizontal line $0\,a\,b\,c$ and a vertical passing through the highest point of the curve.

CYCLE, FREQUENCY, ALTERNATION, PERIOD

6. In all the curves shown in Figs. 3 to 6, the current passes through a set of positive values, while the interval of time, represented by the distance $0\,a$, is elapsing, and through a similar negative set during the interval represented by the distance $a\,b$. This operation of passing

through a complete set of positive and negative values is repeated over and over in equal intervals of time.

The complete set of values that an alternating current passes through repeatedly as time elapses is called a **cycle.** A cycle would therefore be represented by the set of values that the current passes through while the time represented by the distance $0\,b$ elapses.

7. The number of cycles passed through in 1 second is called the **frequency** of the current. For example, if the current had a frequency of 30, it would mean that it passed through 30 complete cycles or sets of values per second. In this case the distance $0\,b$ would, therefore, represent an interval of $\frac{1}{30}$ second, and the time occupied for each half wave, or the distance $0\,a$, would be $\frac{1}{60}$ second. The frequency is usually denoted by the letter n, although the letter f is sometimes used and the symbol $\sim$ was adopted in some of the earlier works on alternating currents. Frequencies employed in alternating-current work vary greatly and depend largely on the use to which the current is to be put. For lighting work, frequencies from 60 to 125 or 130 are in common use. For power-transmission purposes, the frequencies are usually lower, varying from 60 down to 25, or even less. Very low frequencies cannot be used for lighting work, because of the flickering of the lamps. Several of the large companies have adopted 60 as a standard frequency for both lighting and power apparatus. This is well suited for operating both lights and motors, and enables both to be run from the same machine—a considerable advantage, especially in small stations. The high frequencies of 125 to 130 are going out of use except in stations that operate lights exclusively.

8. An **alternation** is half a cycle. An alternation is, therefore, represented by one of the half waves, and there are two alternations for every cycle.

Instead of expressing the frequency of an alternator as so many cycles per second, some prefer to give it in terms of so many alternations per minute. For example, suppose we

have an alternator supplying current at a frequency of 60, i. e., 60 complete cycles per second, or 3,600 per minute. Since there are two alternations for every cycle, the machine might be said to give 7,200 alternations per minute. The method of expressing the frequency as so many cycles per second is, however, the one most commonly used.

9. The time of duration of one cycle is called its **period.** This is usually denoted by t and expresses the number of seconds or fraction of a second that it takes for one cycle to elapse. If the frequency were 60, the period would be $\frac{1}{60}$ second, or, in general,

$$\text{frequency} = \frac{1}{\text{period}}$$

or

$$n = \frac{1}{t} \qquad (1)$$

10. Two alternating currents are said to be **in synchronism** when they have the same frequency. Two alternators would be said to be running in synchronism when each of them was delivering a current that passed through exactly the same number of cycles per second. Although, strictly speaking, two E. M. F.'s are in synchronism when they have the same frequency, the term in synchronism as generally used carries with it the idea that not only do the two E. M. F.'s have the same frequency, but also that they are in phase, i. e., they are in step or pass through their maximum and minimum values simultaneously as explained later.

SINE CURVES

11. The variation of an alternating current, as time elapses, may always be represented by a wave-like curve, such as those shown in the previous diagrams, such curves being easily obtained from the alternators by several well-known methods. The current at any instant may thus be obtained. In order, however, to study the effects of an alternating current, it is necessary to know the law according to which this curve varies. In the case of the irregular

curves shown in Figs. 3, 4, and 5, the law giving the relation between the time and the value of the current is so complicated that it renders calculations too involved. A great many alternators give E. M. F. and current curves that closely resemble that shown in Fig. 6, and the law that this curve follows is quite simple. Such a curve may be constructed as follows: Suppose a point p, Fig. 7, moves

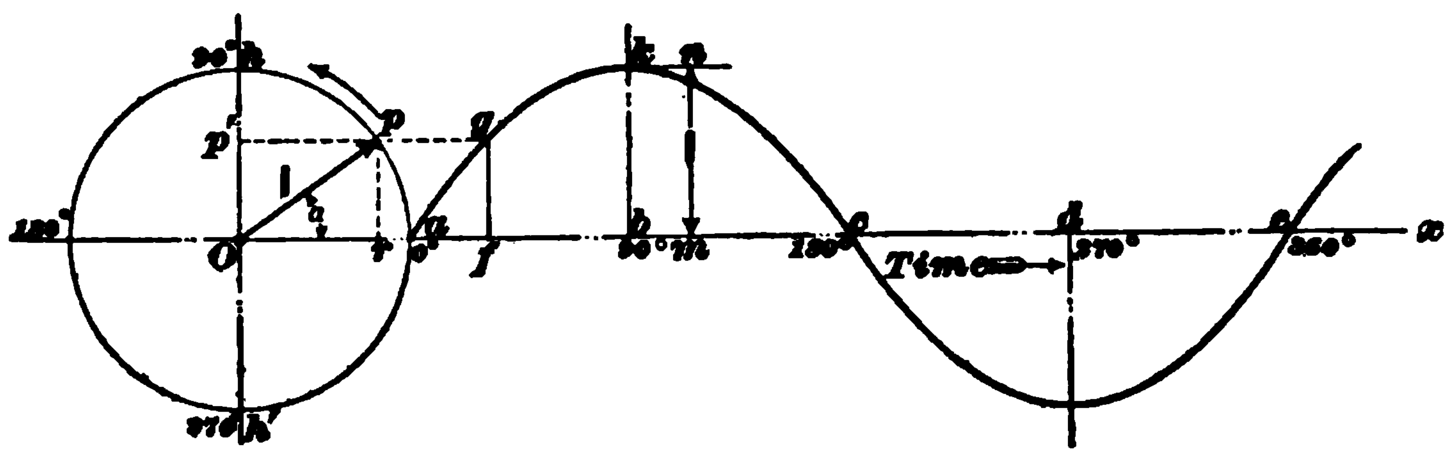


FIG. 7

uniformly around a circle in the direction of the arrow, starting from 0°. The angle α (pronounced alpha) will uniformly increase from 0° to 180° and from there to 360°, or back to 0°, and so on. Take the instant when the point is in the position shown and project it on the vertical through O. The line $Op' = rp$, which is the projection of Op, will be proportional to the sine of the angle α, because $\sin\ \alpha = \frac{rp}{Op}$ and Op remains constant. When $\alpha = 90°$, the projection, or sin α, is proportional to $O\,h$; when at 180° or 360° it is zero, and when at 270° it is proportional to $O\,h'$. All the values of the projection of the line Op from 0° to 180° are positive or above the horizontal, and those from 180° to 360° are negative or below the horizontal. As the point p revolves, p' moves from O to h, back through O to h', and then back to O when the point p has reached 0° again. The way in which the sine (or length of the line Op') varies as the point p revolves may be shown by laying out along the line $O\,x$ distances representing the time that it takes the point p to turn through various values of the angle α and erecting perpendiculars equal to the values of the sine corresponding to these angles. At the point a

the value of the projection of Op would be zero. At the instant shown in the figure the value of the sine is $rp = Op'$. Lay off the distance af, representing the time required for the point to move from 0° to p, and erect a perpendicular fg equal to rp. The distance ab represents the time required for p to move through 90°, and the perpendicular bk is equal to $Oh = Op$. A number of points may be found in this way and the half wave akc drawn in. The negative half wave is exactly the same shape, but, of course, is drawn on the lower side of the horizontal. A curve constructed in this manner is known as a **sine curve,** because its perpendicular at any point is proportional to the sine of the angle corresponding to that point. The sine of the angles 0°, 180°, 360° is zero; hence, at the points corresponding to these angles, the curve cuts the horizontal, i. e., the curve passes through its zero value. At 90° the curve passes through its positive maximum value, and at 270° it passes through its negative maximum. The maximum value of the curve $bk = Op$ is called its **amplitude,** and the curve varies between the limits $+bk$ and $-bk$.

12. If an alternating current or E. M. F. is represented by a sine curve constructed as above, the maximum value that the current or E. M. F. reaches during a cycle will be represented to scale by the vertical bk, and the value at any other instant during the cycle will be $bk \sin \alpha$, where α is the angle corresponding to the instant under consideration. The law that such a curve follows is therefore quite simple, and fortunately such a curve represents quite closely the E. M. F. and current waves generated by a large class of alternators. Even where the curves do not follow the sine law exactly, it is sufficiently accurate for most practical purposes to assume that they do. In calculations connected with alternating currents, it is therefore usual to assume that the sine law holds good. The wave shown in Fig. 7 may therefore be taken to represent the way in which an alternating current varies. During the time repsented by the distance ac, one complete cycle occurs. The

maximum value of the current is represented by the vertical, or ordinate, $I = bk$, and the current passes through a certain number of these cycles every second, depending on the frequency n of the alternator. Since the revolving line $Op = bk = I$, it follows that Op represents the maximum value of the current, and its projection on Oh at any instant represents the value of the current at that instant.

13. The student should always keep in mind the fact that in an alternating-current circuit there is a continual surging back and forth of current, rather than a steady flow, as in the case of direct current, and it is this continual changing of the current that gives rise to most of the peculiarities that distinguish the action of alternating currents from direct.

PROPERTIES OF SINE CURVES

14. By examining Fig. 7, it will be seen that every time the point p makes one complete revolution, the sine curve passes through one complete cycle, and the time that it takes p to make one revolution corresponds to the period. The number of revolutions that the point p makes in 1 second would therefore be equal to the frequency n. It is well to note, in passing, that the sine curve is much steeper when it crosses the axis than when it is near its maximum values; in other words, the sine of the angle is changing more rapidly when near 0° and 180° than when near 90° and 270°.

ADDITION OF SINE CURVES

15. If a line carrying a continuous current is split into two or more branches, the current flowing in the main line is found by taking the sum of the currents in the different branches. For example, suppose a pair of electric-light mains feeds three circuits, taking 5, 10, and 50 amperes; the current in the mains would be found by simply taking the sum of these, i. e., 65 amperes. This method, however, cannot, as a general rule, be applied to alternating-current

circuits, and it is necessary, therefore, to study carefully the methods of adding together two or more alternating currents or E. M. F.'s.

16. The method of adding together two alternating E. M. F.'s represented by sine curves is shown in Fig. 8.

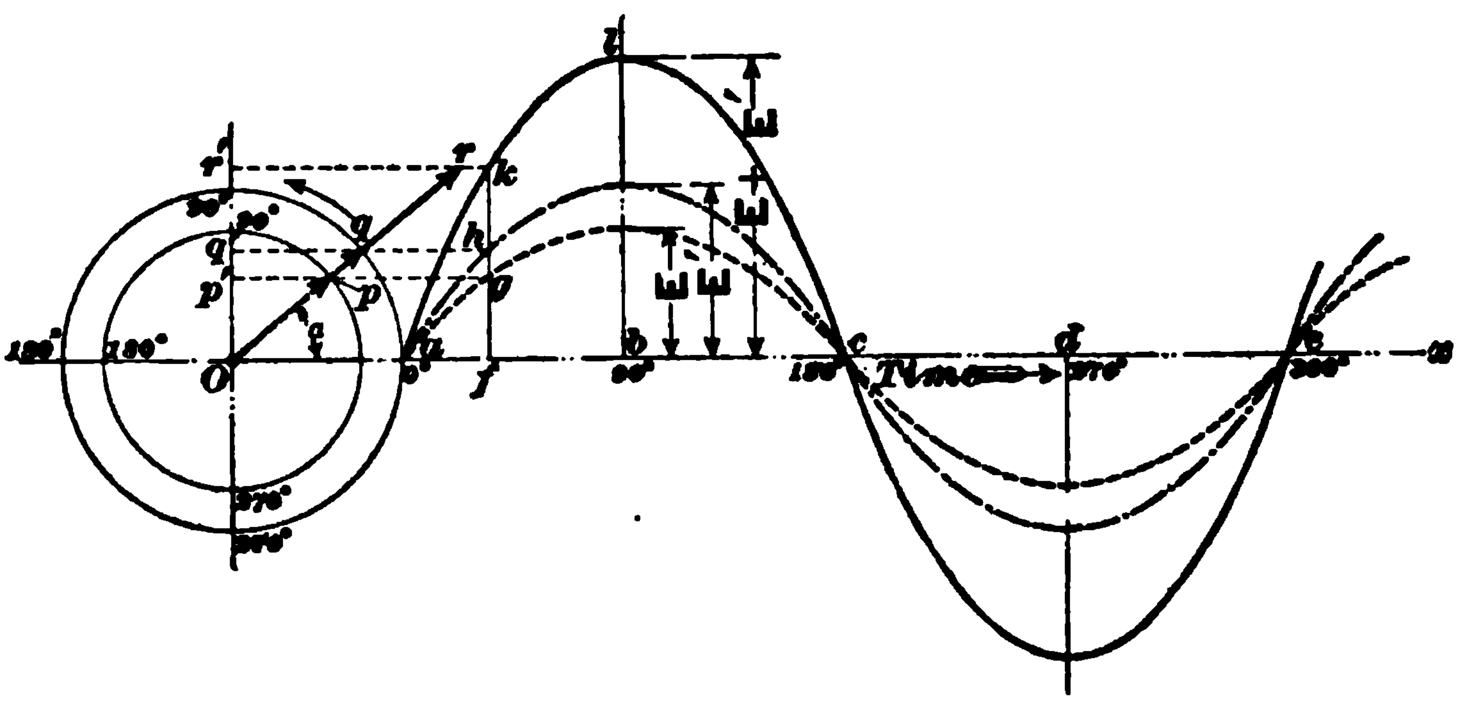


FIG. 8

One E. M. F. is represented to scale by the radius Op; that is, the radius Op is laid off to represent the maximum value **E** that the E. M. F. reaches during a cycle. The point p is supposed to revolve uniformly around the inner circle, and the corresponding sine curve is shown by the dotted wave. The other E. M. F. has its maximum value **E'** represented by the radius Oq, which revolves uniformly around the outer circle, generating the sine wave shown by the dot-and-dash line. Both points are supposed to revolve at exactly the same speed and to start from 0° at the same instant; in other words, the frequency of both is the same, or they are in synchronism. Since both points start from 0° at the same instant and revolve at the same rate, it follows that both the E. M. F. curves will vary together. They will come to their maximum values at the same instant and will pass through zero simultaneously. When two or more alternating E. M. F.'s or currents vary together in this way, they are said to be **in phase** with each other. The curve

representing the sum of these two E. M. F.'s is easily found by adding together the instantaneous values of the separate E. M. F.'s, thus giving the sine curve shown by the full line. For example, take any instant represented by the point f on the line $O\,x$; the ordinate, or vertical, $f\,g$ represents the instantaneous value of the E. M. F. **E**, and the ordinate $f\,h$ represents the instantaneous value of **E**'. The value of their sum at this particular instant is therefore found by adding $f\,g$ and $f\,h$, giving $f\,k$, and locating the point k on the required curve. The maximum ordinate of this resultant curve is $b\,l = \mathbf{E} + \mathbf{E}'$. This curve representing the sum of the two original E. M. F.'s is in phase with **E** and **E**', and is also a sine curve; hence, it may also be represented by a line revolving about the point O, provided this line is so taken that its projection on the vertical is at all instants equal to the sum of the projections of the two original lines $O\,p$ and $O\,q$. Since the points p and q are in line with each other, it follows that if we produce $O\,q$ to r, making $O\,r = O\,p + O\,q$, the projection of $O\,r = O\,r'$ will be equal to the sum of the projections of $O\,p$ and $O\,q$, i. e., $O\,r' = O\,p' + O\,q'$. It follows, then, from the above, that if the line $O\,r$ were to revolve uniformly around O at the same rate as $O\,p$ and $O\,q$, the curve representing the sum of the two E. M. F.'s would be generated.

17. The following may be summarized from the foregoing:

1. *The curve representing the sum of two or more sine curves may be obtained by adding together the ordinates representing the instantaneous values of the original curves.*

2. *If the two or more curves that are added are of the same frequency (as is usually the case), the resultant also will be a sine curve.*

3. *Two or more alternating E. M. F.'s or currents of the same frequency are said to be in phase with each other, when they reach their maximum and minimum values at the same instant.*

4. *The resultant sine curve representing the sum of two or more sine curves of the same frequency may be generated by a line revolving uniformly, and of such length and so located with reference to the lines generating the original curves that its projection on the vertical will at all instants be equal to the sum of the projections of the two original revolving lines.*

18. In Fig. 8, the line $Or = Op + Oq$ generates the resultant curve, and since Op and Oq are in phase with each other, it is seen that Or is found by simply taking the sum of the two original lines Op and Oq. In other words, when two alternating E. M. F.'s or currents are in phase, they may be added together in the same way as direct currents, but if they are not in phase, this cannot be done. It is quite possible in alternating-current circuits to have the current and E. M. F. out of phase with each other, and the same is true regarding two or more E. M. F.'s and two or more currents. Suppose that an alternator is forcing current through a circuit. Every wave of E. M. F. will be accompanied by a corresponding wave of current, and hence the current and E. M. F. will always have the same frequency. There are a number of causes that may prevent the current and E. M. F. from coming to their maximum and minimum values at the same instant, and the current may lag behind the E. M. F. or may be ahead of it. In the case of two alternators feeding current into a common circuit, one current may lag behind the other, or the E. M. F. produced by an alternator may not be in phase with its current. The effects of this difference of phase must be taken into account in alternating-current work, as it gives rise to a number of peculiar effects not met with in connection with direct currents. Of course, in the case of direct currents there is no change taking place in the currents or E. M. F.'s; consequently, in direct-current circuits, there cannot be any phase difference between current and E. M. F.

19. The effects of this difference in phase will be seen more clearly by referring to Fig. 9. The two E. M. F.'s E

and E′ are represented by the revolving lines Op and Oq as before. In this case, however, the E. M. F. E′ starts from 0° before E, and the two are displaced by the angle ϕ (phi); in other words, the point p does not start from 0° until the point q has turned through an angle ϕ. After this, the two revolve in synchronism, and the angle ϕ remains constant, while the angle α is continually changing, as before. The E. M. F. E is therefore lagging behind E′, and the two E. M. F.'s are said to be **out of phase.** It might also be said that the E. M. F. E′ was ϕ degrees ahead or in advance of E, or that E lagged ϕ degrees behind E′. If E lagged one-half a cycle behind E′, the angle of lag would be 180°,

FIG. 9

and if it were said that E lagged 90° behind E′, it would mean that E came to its maximum or minimum value just one-fourth of a period later than E′. The dot-and-dash curve, as before, represents E′, and the dotted curve represents E. The two curves, however, no longer cross the horizontal, or come to their maximum, at the same instant. The dotted curve starts in at the point c, a distance ac behind the curve representing E′. Since time is measured in the direction of the arrow, the point c represents an instant that is later than the point a. In other words, the curve representing E does not start until an interval of time, represented by ac, has elapsed after the starting of the dot-and-dash curve, i. e., the dotted curve is lagging

behind the other. The distance $a\,c$ is equivalent to the time that it would take p or q to turn through the angle ϕ. The sum of the two curves is found, as before, by adding the ordinates; thus $h\,k + h\,l = h\,m$, and the resultant curve shown by the full line is obtained. It will be noticed that this is a sine curve, but it is in phase with neither of the original curves, also that its maximum value E'' is not as great as in the case shown in Fig. 8. The resultant curve has, however, the same frequency as the others. The revolving line that will generate this curve must have its projections on the vertical equal to the sum of the projections of the other two. This condition is fulfilled by the line $O\,r$, which is the diagonal of the parallelogram formed on the two sides $O\,p$ and $O\,q$. That this is the case will be seen by referring to the figure. The projection of $O\,p$ is $O\,p'$ and of $O\,q$, $O\,q'$. The projection of the diagonal $O\,r$ is $O\,r'$; but $q'\,r' = O\,p'$; hence, $O\,r' = O\,q' + O\,p'$, and if the diagonal $O\,r$ were to revolve at the same rate as $O\,p$ and $O\,q$, the full-line curve would be generated. The maximum value of this curve E'' is equal to $O\,r$, and the diagonal $O\,r$ not only gives the maximum value of the resultant curve, but also gives its phase relation in regard to the two original curves. In this case $O\,r$ lags behind $O\,q$ by the angle β (beta), and the distance $a\,b$ represents the interval of time that is required for the line $O\,r$ to swing through the angle β.

20. The important points in the preceding may then be summarized as follows:

1. *In alternating-current systems, two or more currents or E. M. F.'s may not come to their maximum and minimum values at the same instant, in which case they are said to be out of phase or to differ in phase.*

2. *Phase difference is usually expressed by an angle (in most cases denoted by the Greek letter ϕ). If this angle is measured forwards, in the direction of rotation, it is called an* **angle of lead,** *or* **angle of advance;** *if measured backwards, it is called an* **angle of lag.**

3. *Two sine curves not in phase may be added together by adding their ordinates. If the two original curves are of the same frequency, the resultant curve will be also a sine curve, but differing in phase from the other two.*

4. *The maximum value of the resultant curve is given by the diagonal of the parallelogram constructed on the lines representing the maximum values of the original curves. This diagonal not only gives the maximum value of the resultant curve, but also determines its phase relation.*

21. From the foregoing it will be seen at once that in adding alternating currents and E. M. F.'s, account must be taken not only of their magnitude, but also of their phase relation, and they can be added numerically only when they are in phase, as in the case of direct currents.

22. As an example of the addition of two alternating currents, suppose a circuit is divided as shown in Fig. 10.

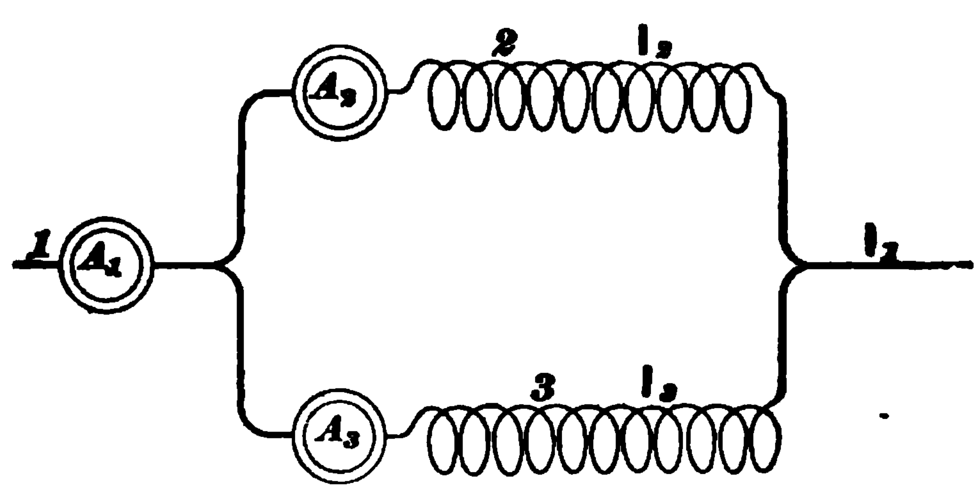


FIG. 10

The main circuit *1* is divided into the branches *2* and *3*, and ammeters A_1, A_2, and A_3 are placed in the branches. If a continuous current were flowing, the reading of A_1 would be equal to the sum of the readings of A_2 and A_3. This, however, would not be the case if an alternating current were flowing, unless the currents in the two branches happened to be exactly in phase. Generally speaking, they would not be in phase, and the reading of A_1 would be less

than the sum of A_2 and A_3. The relation between the three currents would be as shown in Fig. 11, where $\mathbf{I}_1$, the reading of A_1, is the diagonal of the parallelogram formed by $O q$ and $O p$, representing the readings of A_2 and A_3, respectively. These lines can all be laid off to scale, so many amperes per inch, and the angles of phase difference readily determined.

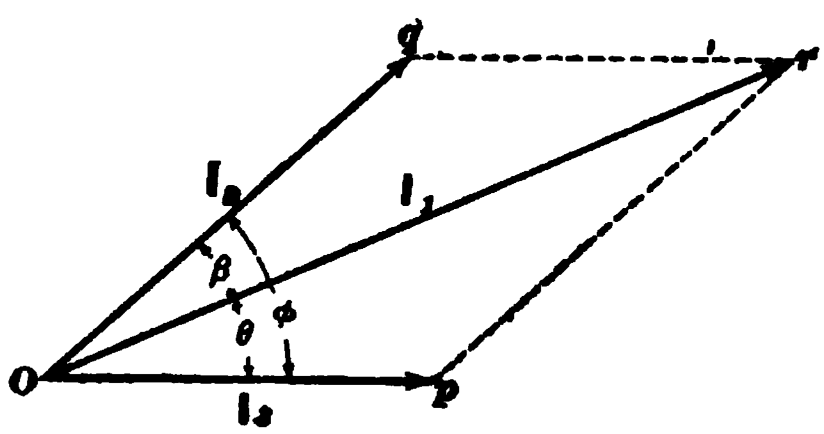


FIG. 11

In this case ϕ is the phase difference between the current in the branches *2* and *3*, while the main current is $\beta°$ behind $\mathbf{I}_2$ and $\theta°$ (theta) ahead of $\mathbf{I}_3$. The resultant current represented by $O r$ is smaller than it would be if $O q$ and $O p$ were in

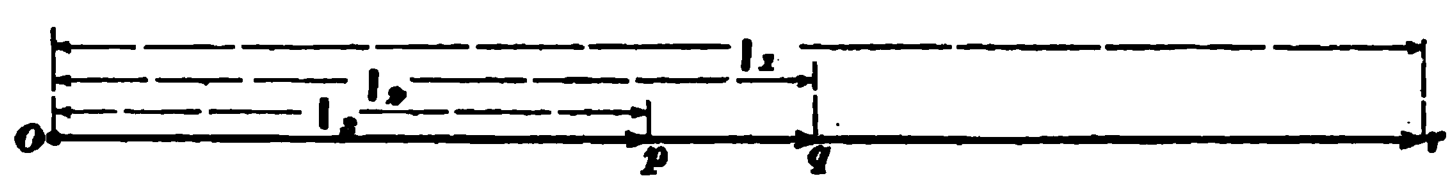


FIG. 12

phase. If $O p$ and $O q$ were in phase, they could be added together directly, and the resultant would be $O r$, as shown in Fig. 12. Here the angle of lag has become zero, and the parallelogram has reduced to a straight line.

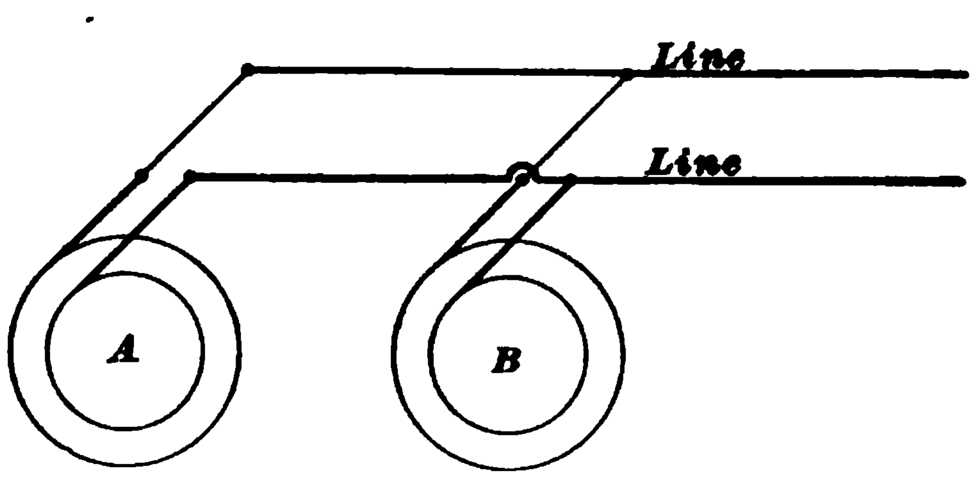


FIG. 13

23. A practical example of the addition of two alternating currents is shown in Fig. 13 where two alternating-

current motors *A* and *B* are supplied with current from the same line. In this case, the two motors *A* and *B* take currents that will in all probability be out of phase and the actual current flowing in the line will be found by taking the geometric sum of the two separate currents, as explained in the preceding example.

24. Alternating E. M. F.'s are added in the same way as currents. If it were possible to operate two alternators *A* and *B*, Fig. 14, in series, one giving an E. M. F.

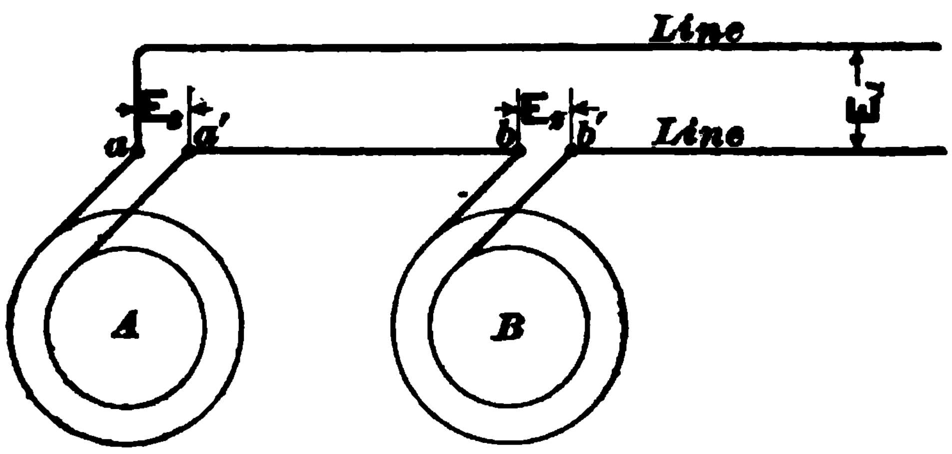


FIG. 14

E_2 and the other E_3 volts, the E. M. F. E_1 obtained across the mains would not generally be equal to $E_2 + E_3$, but would be the resultant sum, as shown by the parallelogram, Fig. 15. If *A* and *B* were continuous-current dynamos, or if E_2 and E_3 were exactly in phase, E_1 would be equal to the sum of E_2 and E_3. On account of this effect of the difference in phase between E_2 and E_3, the sum of

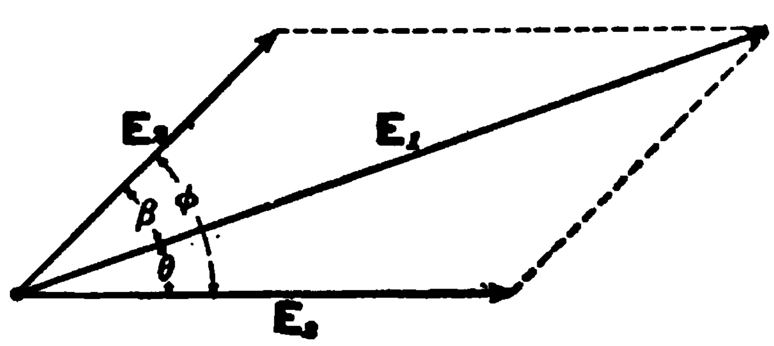


FIG. 15

the readings of voltmeters connected across *a*, *a'* and *b*, *b'* will be greater than the reading obtained by a voltmeter connected across the mains. Alternators operated in series would have to be rigidly connected, otherwise the phase relation between their E. M. F.'s would be continually changing.

TWO-PHASE AND THREE-PHASE SYSTEMS

25. If the angle of lag between two currents is zero, they are said to be in phase.

If the angle of lag between two currents is 90°, they are said to be at **right angles,** or **in quadrature.**

If the angle of lag is 180°, they are said to be **in opposition.**

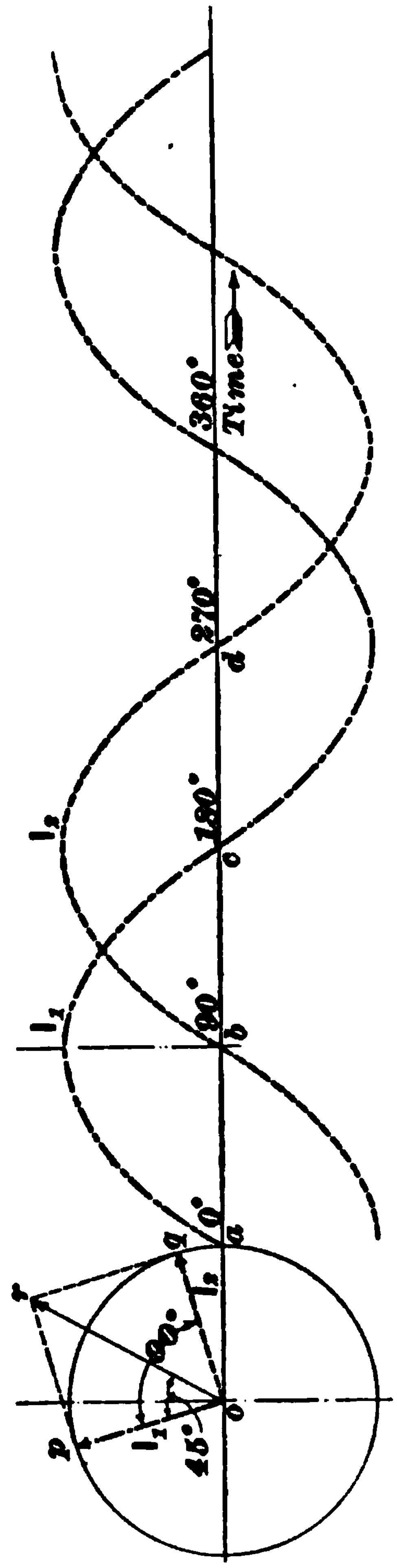


FIG. 16

Fig. 16 shows two current waves at right angles or in quadrature, the current I_2, represented by the dotted line, lagging 90°, or ¼ cycle, behind I_1. If these two currents were fed into a common circuit, the resultant current would be represented by the diagonal *o r*, and this current would lag 45° behind I_1.

26. It will be seen by examining Fig. 16 that at the instant I_1 is at its maximum value, I_2 is passing through zero. If each of these currents were fed into separate lines, a **two-phase,** or **quarter-phase, system** would be obtained, i. e., there would be two distinct circuits, fed from one dynamo, the currents in the two circuits differing in phase by 90°, or one-fourth of a period. Such systems are in common use for operating motors, and will be more fully explained in connection with alternators. Alternators for use with such systems are usually provided with two sets of windings on their armatures, so arranged that when one set is generating its maximum E. M. F., the other is passing through zero.

27. Systems in which three currents are employed are also in common use in connection with power-transmission plants. These currents differ in phase by 120°, or one-third of a cycle, and constitute what is known as a **three-phase system.** Such an arrangement is shown in Fig. 17, where the three equal currents I_1, I_2, and I_3 are displaced in phase by 120°. The corresponding sine curves are also shown, the dotted line I_3 lagging 120° behind the full line I_1, and the dot-and-dash line I_2 lagging 120° behind I_3. In such a case, where the three currents are equal, the resultant sum is at all instants equal to zero. This may be seen from the curves, $g\,l$, for example, being the equal and opposite of $g\,h + g\,k$, and $2\,d\,e$ the equal and opposite of $d\,f$. It is well to bear this property of a balanced three-phase system in mind, as it is taken advantage of in connection with three-phase armatures and in three-phase power-transmission lines. The above would not be true if the system were unbalanced, i. e., if I_1, I_2, and I_3 were not all equal; but in most cases where these systems are used, it is tried as far as possible to keep the currents in the different lines equal. It should also be noted that in such a system when the current in one line is zero, the currents in the other two lines are equal and are flowing in opposite directions. When the current in one circuit is at its maximum value, the currents in the other two are in the opposite direction and one-half as great.

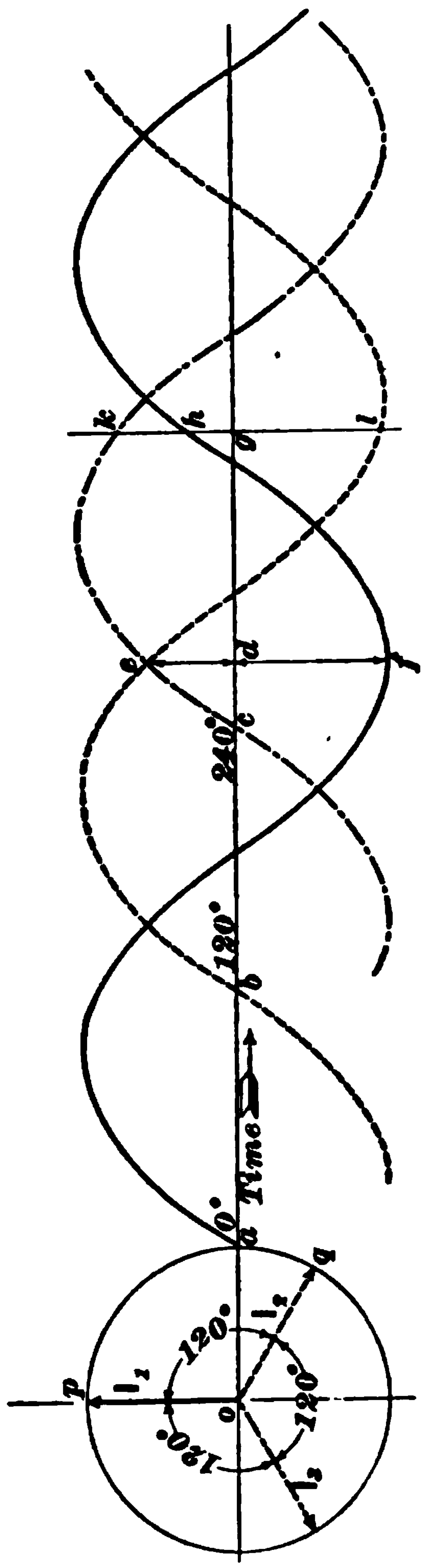


FIG. 17

COMPOSITION AND RESOLUTION OF CURRENTS AND E. M. F.'S

28. It has been shown that a sine wave may always be represented by a line revolving uniformly around a point and showing to scale the maximum value of the E. M. F. or current. The projection of this line on the vertical at any instant gives the instantaneous value of the E. M. F.

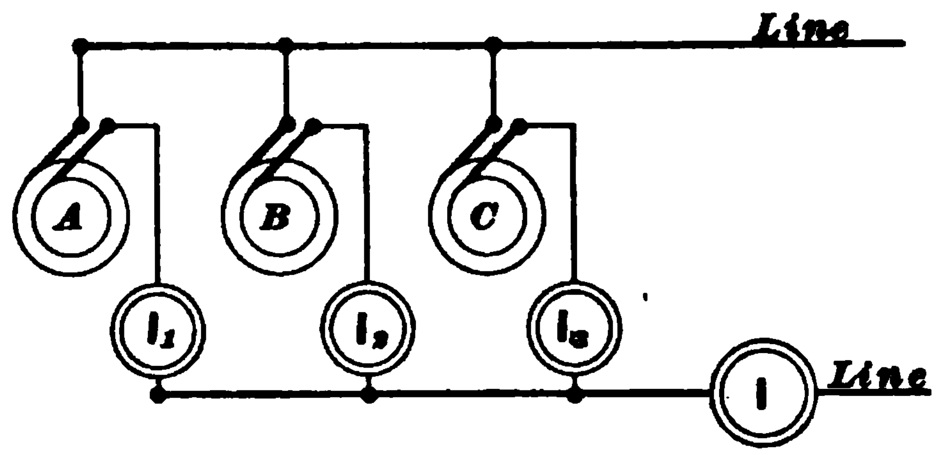


FIG. 18

or current. In working out problems in connection with alternating currents, it is not necessary to draw in the sine curves, but to use simply the line representing the curve. It has already been shown how currents and E. M. F.'s may be added by using these lines. In fact, alternating currents and E. M. F.'s are added and resolved into components in just the same way as forces are treated in mechanics, by means of the parallelogram of forces. What holds true with regard to two currents also applies to three or more, in this case the polygon of forces being employed. An example of this is shown in Fig. 18. Three alternating-current motors *A*, *B*, and *C* are in parallel, and supplied with current from the same line. The three currents differ in phase, and their amounts are given by the ammeters I_1, I_2, I_3. Required, the current flowing in the main circuit. This will be the resultant sum of I_1, I_2, and I_3. Lay off $O a$, $O b$, and $O c$, Fig. 19, to represent the three currents to scale and in their proper phase relation. From a draw $a c$ equal and parallel to $O b$, and from e draw $e d$ equal and parallel to $O c$. Join $O d$; then $O d$ will represent the resultant current

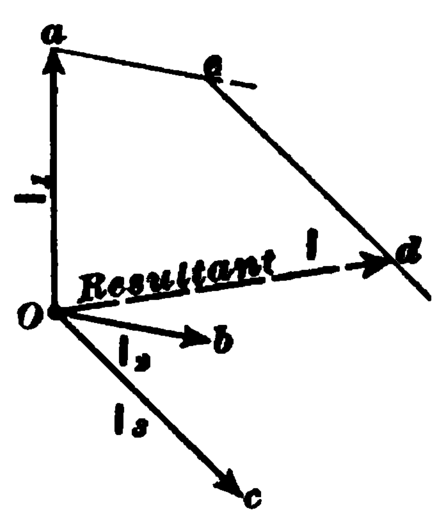


FIG. 19

to the same scale that $O a$, $O b$, and $O c$ represent I_1, I_2,

and I_3. In other words, Od will represent to scale the reading of the ammeter I placed in the main line. The angles giving the phase differences between the different currents can usually be calculated when the constants of the different circuits are known. Methods for calculating the angles of phase difference will be given later. If the three currents represented by Oa, Ob, and Oc should all happen to be in phase with one another, their resultant sum can be obtained by simply adding them up numerically.

29. Alternating E. M. F.'s and currents may be resolved into two or more components in the same way that forces are resolved in mechanics, by reversing the process of composition. For example, in Fig. 20, we have the current represented by Oa resolved into two components Ob and Oc. The two currents represented by Ob and Oc, differing in phase by the angle ϕ, will therefore combine to produce the current represented by Oa.

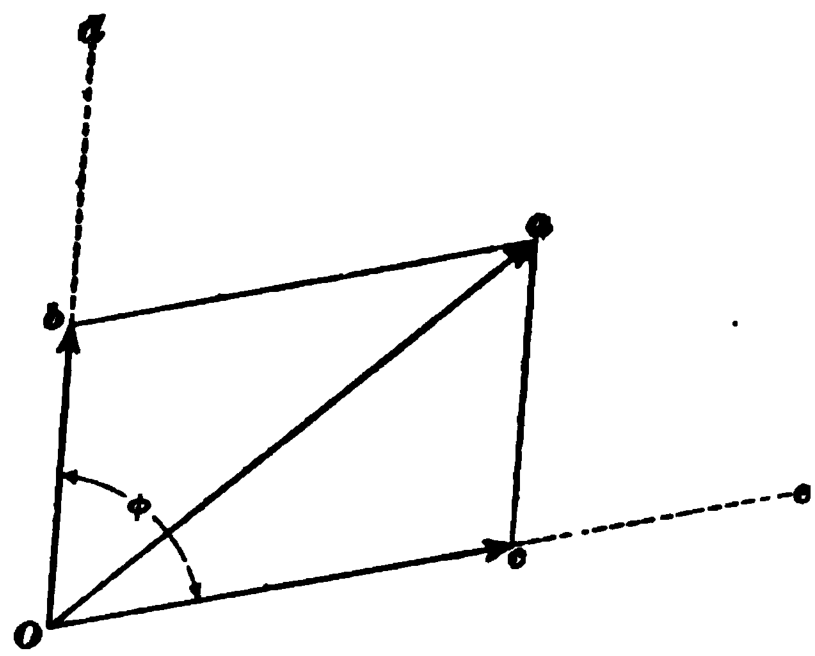


FIG. 20

EXAMPLES FOR PRACTICE

1. Two currents, one of 40 amperes and the other of 50 amperes, differing in phase by 30°, unite to form a third current. Required, the value of this current. Ans. 87 amperes, nearly

2. Construct a curve that will represent the E. M. F. of an alternator generating a maximum of 300 volts at a frequency of 60. Use 1 inch per 100 volts for the vertical scale and 1 inch equal to $\frac{1}{100}$ second for the horizontal.

3. Represent two E. M. F.'s of same frequency, one of 200 volts maximum and the other of 150 volts maximum, the latter lagging behind the former by an angle of 60°. Draw the two sine curves

representing these E. M. F.'s in their proper relation to each other, and add these together to obtain the resultant curve. Find the maximum value of this resultant and compare its value with that obtained by taking the diagonal of the parallelogram constructed from the two component E. M. F.'s. Ans. Resultant E. M. F. = 304 volts

NOTE.—The student should bear in mind that in all the foregoing cases the waves of current and E. M. F. are supposed to follow the sine law.

MAXIMUM, AVERAGE, AND EFFECTIVE VALUES OF SINE WAVES

30. During each cycle, an alternating current passes through a large range of values from zero to its maximum. These instantaneous values are, as a rule, used very little in calculations. It is necessary to have it clearly understood what is meant when it is said that a current of so many amperes is flowing in a circuit or that an alternator is supplying a pressure of so many volts. When it is stated that an alternating current of, say, 10 amperes is flowing in a circuit, some average value must be implied, because, as a matter of fact, the current is continually alternating through a range of values. It has become the universal custom to express alternating currents in terms of the value of the continuous current that would produce the same heating effect in the circuit; as, for example, if the alternating current were 10 amperes, it would mean that this alternating current would produce the same heating effect as 10 amperes continuous current.

31. Suppose the sine curve, Fig. 21, represents the variation of an alternating E. M. F.; there are three values that are of particular importance:

1. The **maximum value**, or the highest value that the E. M. F. reaches, is given by the ordinate **E**. This maximum value is not used to any great extent, but it shows the maximum to which the E. M. F. rises, and hence would indicate the maximum strain to which the insulation of the alternator would be subjected.

2. The **average value** of a sine curve is the average of all the ordinates of the curve for one-half a cycle. For example, in Fig. 21, the average ordinate of the curve *a f b*

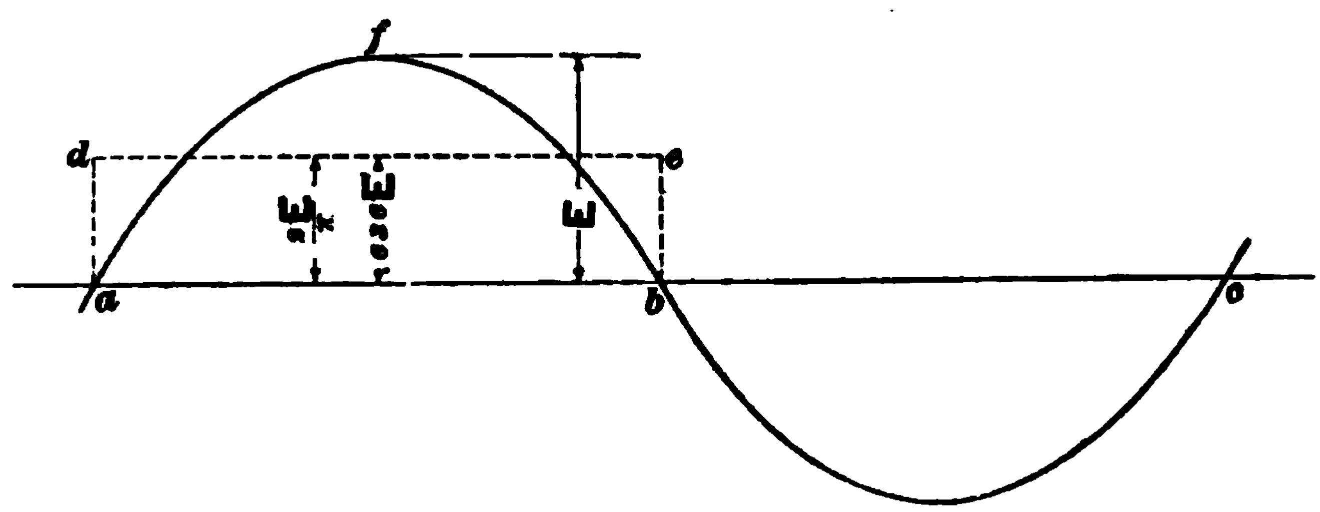


FIG. 21

would be that ordinate *a d* which, multiplied by the base *a b*, would give a rectangle *a b e d* of the same area as the surface *a f b*. The average value taken for a whole cycle would be zero, because the average ordinate for the negative wave would be the equal and opposite of the positive ordinate. In the case of a sine curve, this average value always bears a definite relation to the maximum value. If E is the maximum value, the average value is $\frac{2\,E}{\pi}$, or .636 E.* The average value is used in some calculations, but, like the maximum value, its use is not very extended. The relation between the average and maximum value, however, is used considerably and should be kept in mind.

3. The **effective value** of an alternating current may be defined as that value which would produce the same heating

* The fact that the average value of the sine is .636, or $\frac{2}{\pi}$, may be proved exactly by means of calculus, but the student can easily verify it approximately by taking the values of the sine of the angles from 0° to 90° from a trigonometric table, adding these together, and dividing by the number of values. The average so found will be very nearly .636. The value can be obtained with a fair degree of accuracy by adding the sines of every fifth degree, as, for example, 0°, 5°, 10°, 15°, etc.

effect in a circuit as a continuous current of the same amount. This effective value is the one universally used to express alternating currents and E. M. F.'s. It always bears a definite relation to the maximum value. When ammeters or voltmeters are connected in alternating circuits, they always read effective amperes or volts, though, for purposes of illustration, we have assumed in some of the previous examples connected with the composition and resolution of E. M. F.'s and currents that maximum values are indicated. This effective value is not the same as the average value (.636 maximum), as might at first be supposed, but it is slightly greater, being equal to .707 times the maximum value. If a continuous current I be sent through a wire of resistance R, the wire becomes heated, and the power expended in heating the wire is $W = I^2 R$ watts, or is proportional to the square of the current. If an alternating current be sent through the same wire, the heating effect is at each instant proportional to the square of the current at that instant. The average heating effect will therefore be proportional to the average of the squares of all the different instantaneous values of the current, and the effective value of the current will be the square root of the average of the squares of the instantaneous values. The effective value is for this reason sometimes called the square-root-of-mean-square value. It is also frequently called the *virtual value*. Suppose, for example, a circuit in which an alternating current of 10 amperes maximum is flowing. This means that the current is continually alternating between the limits + 10 amperes and − 10 amperes, and passing through all the intermediate values during each cycle. Now, as far as the heating effect of this current is concerned, it would be just the same as if a steady current of .707 × 10, or 7.07 amperes, were flowing, and if an ammeter were placed in the circuit, it would indicate 7.07 amperes. Hereafter, in speaking of alternating E. M. F.'s and currents, effective values will be understood unless otherwise specified.

RELATIONS BETWEEN VALUES

32. The relation between the maximum, average, and effective values will be seen by referring to Fig. 22, the

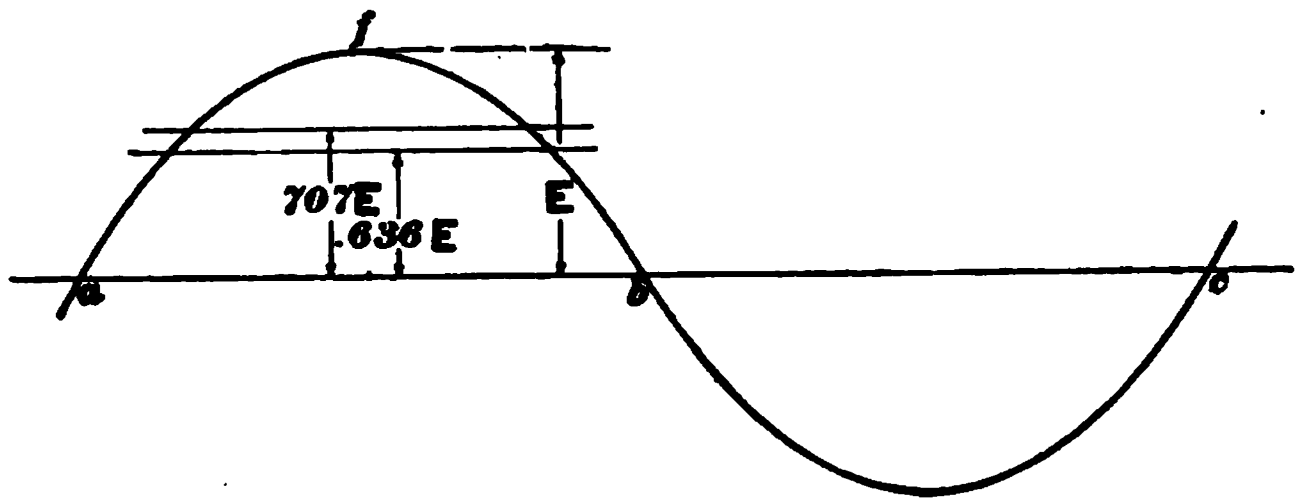


FIG. 22

average ordinate .636 **E** being slightly shorter than the effective .707 **E**. For convenience, the following relations are here given together. They should be kept well in mind, as they are used continually in problems connected with alternating-current work.

Average value = .636 maximum value

Effective value = .707 maximum value, or $\dfrac{\text{maximum value}}{\sqrt{2}}$

Effective value = 1.11 average value

33. Form Factor.—The ratio $\dfrac{\text{effective value}}{\text{average value}}$ is known as the **form factor** of an E. M. F. or current wave, because this ratio depends on the shape of the wave. For a sine wave, it has just been shown that the form factor is 1.11. For a peaked wave, like that shown in Fig. 4, it will be greater than 1.11, and for the flat wave shown in Fig. 2, it will be equal to 1.

34. On account of the importance of the effective value, the following proof is given of the relation: Effective

value = .707 maximum. Let Oa, Fig. 23, represent the maximum value of the sine. The sine at any instant corresponding to the angle α is $ab = Oa \sin \alpha$,

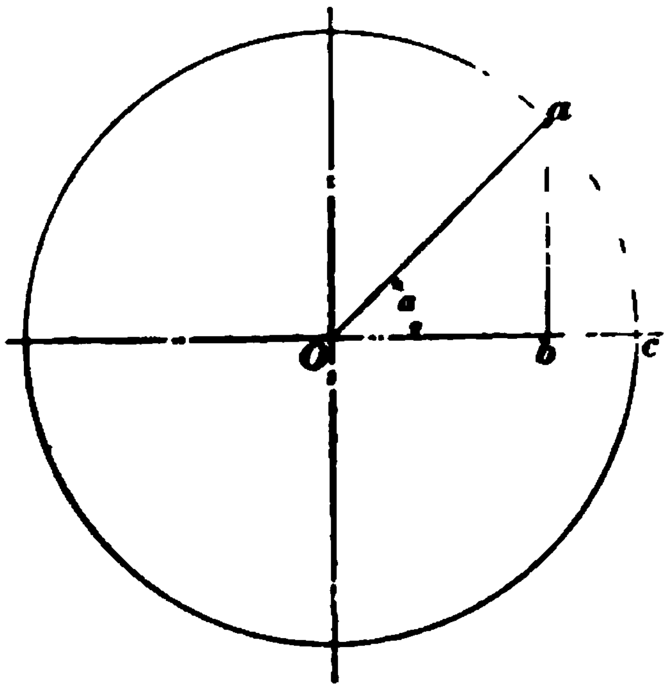


FIG. 23

or

$$\sin \alpha = \frac{ab}{Oa}$$

$$\sin^2 \alpha = \frac{\overline{ab}^2}{\overline{Oa}^2}$$

$$\cos \alpha = \frac{Ob}{Oa}$$

$$\cos^2 \alpha = \frac{\overline{Ob}^2}{\overline{Oa}^2}$$

$$\sin^2 \alpha + \cos^2 \alpha = \frac{\overline{ab}^2}{\overline{Oa}^2} + \frac{\overline{Ob}^2}{\overline{Oa}^2} = \frac{\overline{ab}^2 + \overline{Ob}^2}{\overline{Oa}^2} = \frac{\overline{Oa}^2}{\overline{Oa}^2} = 1$$

Now as the line Oa revolves, thus generating the sine curve, the sine varies from 0 to Oa and the cosine varies from Oc $(= Oa)$ to 0, so that the sine and cosine pass through the same range of values, and consequently the average of the squares of the sine and the cosine must be the same. Since

$$\sin^2 \alpha + \cos^2 \alpha = 1$$

$$\text{av. } \sin^2 \alpha + \text{av. } \cos^2 \alpha = 1$$

From the above,

$$2 \text{ av. } \sin^2 \alpha = 1$$

$$\text{av. } \sin^2 \alpha = \tfrac{1}{2}$$

$$\sqrt{\text{av. } \sin^2 \alpha} = \frac{1}{\sqrt{2}}$$

As the alternating E. M. F. is supposed to follow the sine law, the instantaneous value of the E. M. F. at any instant corresponding to the angle α, is $e = \mathbf{E} \sin \alpha$, where $\mathbf{E}$ is the maximum value; hence,

$$e^2 = \mathbf{E}^2 \sin^2 \alpha$$

$$\text{av. } e^2 = \mathbf{E}^2 \text{ av. } \sin^2 \alpha$$

$$\text{av. } e^2 = \frac{\mathbf{E}^2}{2}$$

$$\sqrt{\text{av. } e^2} = \frac{\mathbf{E}}{\sqrt{2}} = .707 \times \mathbf{E};$$

i. e., *the effective, or square-root-of-mean-square value, is equal to the maximum value multiplied by* $\frac{1}{\sqrt{2}}$, *or* .707.

35. Hereafter, in designating E. M. F.'s and currents we will use heavy-faced type to denote maximum values of E. M. F.'s or currents, and light-faced type to denote the effective values. In most of the previous figures, the values used were maximum values; hence, the heavy-faced letters **E** and **I** were employed. Instantaneous values will be expressed by small italic letters, indicated in the following list of symbols:

$\mathbf{E}$ = maximum E. M. F.;
E = effective, square-root-of-mean-square, or virtual E. M. F.;
e = instantaneous E. M. F.;
$\mathbf{I}$ = maximum current;
I = effective, square-root-of-mean-square, or virtual current;
i = instantaneous current.

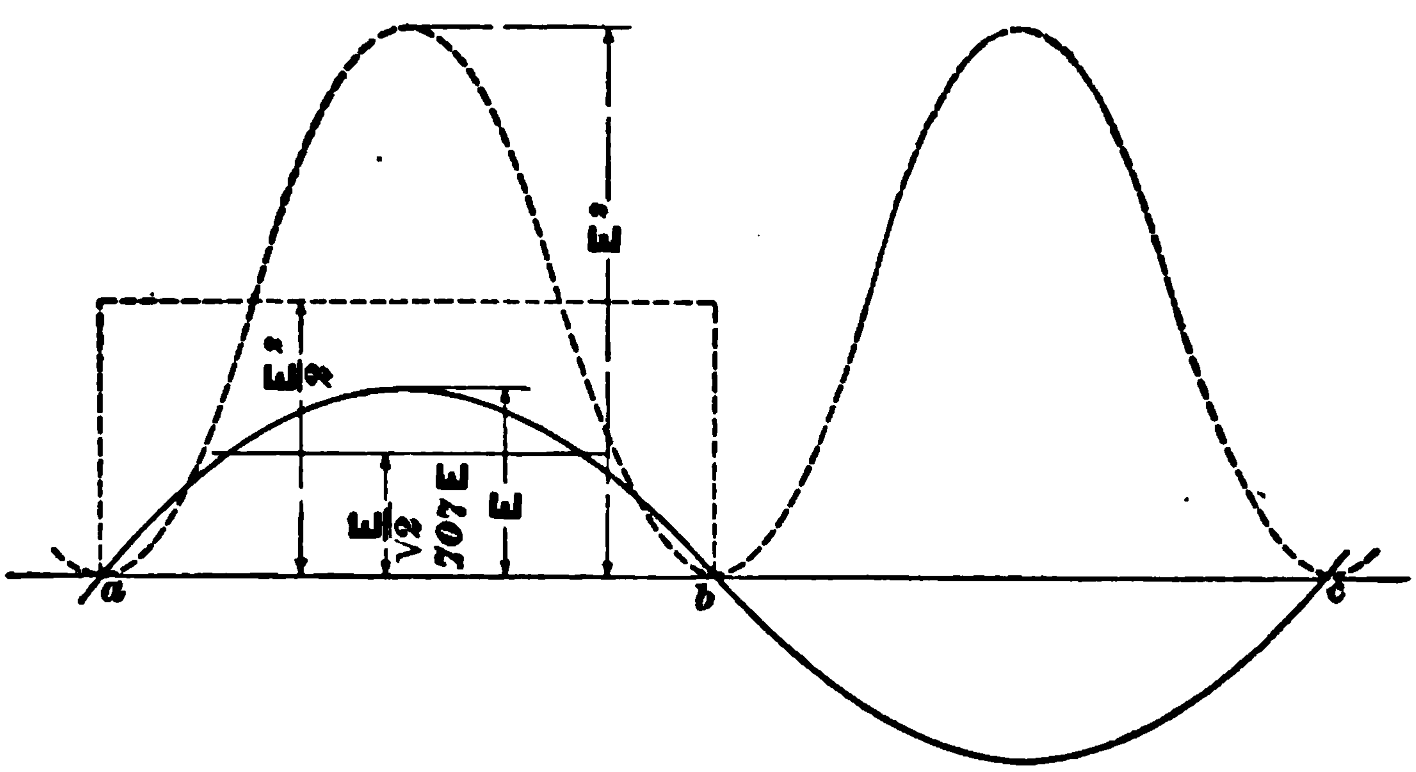


FIG. 24

36. In Fig. 24, the value of the square-root-of-mean-square ordinate is obtained graphically. The dotted curve

is obtained by squaring the ordinates of the sine curve, and the area of the dotted rectangle is equal to the area enclosed by the curve of squares. The height of this ordinate is $\frac{E^2}{2}$, and it represents the average of all the values of e^2. The square root of this gives the effective value of the sine curve: $\frac{E}{\sqrt{2}} = .707\ E$.

37. In the preceding diagrams, showing the composition and resolution of E. M. F.'s and currents by means of the parallelogram, maximum values were used. Since, however, the effective or virtual values always bear a fixed proportion to the maximum, it follows that this construction will apply equally well in case effective values are used. For example, if the two virtual E. M. F.'s E_1 and E_2 are represented by the lines $O\,b$ and $O\,a$, Fig. 25, the line $O\,c$ will represent the resultant virtual E. M. F. to the same scale that $O\,a$ and $O\,b$ represented the original quantities.

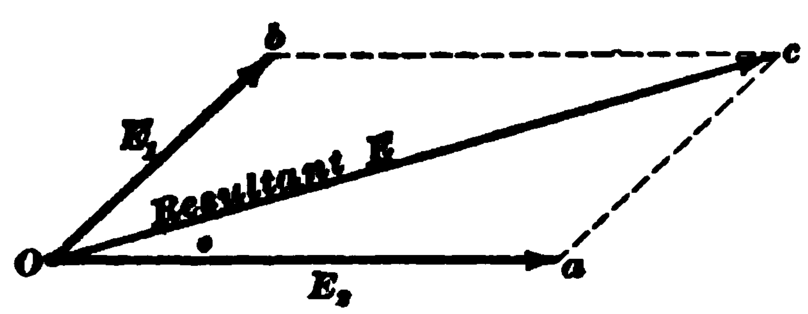


FIG. 25

SELF-INDUCTION AND CAPACITY

38. In most cases the flow of an alternating current through a circuit differs considerably from that of a direct current, even though the E. M. F. is the same in both cases. If a given direct E. M. F. E' is applied to a circuit of resistance R, the current I' that will flow, determined by Ohm's law, is $I' = \frac{E'}{R}$. If an alternating E. M. F. having an effective value E of the same amount as E' be applied to the same circuit, the resulting current I may or may not have the same value as I'. If there were no self-induction or capacity present in the circuit, the alternating current would behave in the same way as the direct current, but in most

cases there is more or less self-induction or capacity present so that the current will not flow in accordance with the simple law that governs direct currents. Most of the devices used in connection with the applications of alternating currents have more or less self-induction; alternating-current motors, arc lamps, transformers, and even the transmission lines, all have it in greater or less amount. Overhead lines of considerable length also have an appreciable amount of electrostatic capacity, and the electrostatic capacity of underground cables is quite large. Under some conditions, certain kinds of alternating-current motors also act as if they had electrostatic capacity. Generally speaking, the effects of capacity are not as commonly met with as those of self-induction, but they are of great importance nevertheless.

39. Effects of Self-Induction.—It has already been shown that any circuit or device that is capable of setting up a magnetic field through itself possesses self-induction. A simple example of this is a coil of wire wound on an iron core. When current is sent around the wire, a magnetic field is set up through the coil. It was further shown that, while the magnetic field is being set up, an E. M. F. is induced in the coil, which is opposed to the current. When the circuit is broken, the lines of force threading the coil collapse, thus inducing an E. M. F. that tends to maintain the current; as long as the current flows steadily, there is no change in the number of lines of force passing through the coil, and, hence, no E. M. F. is induced. This is the state of affairs when a direct current is flowing so that, except at the moment when the circuit is made or broken, the self-induction has no influence on the flow of a direct current. When, however, a current that is continually changing its value, as, for example, an alternating current, is sent through the coil, an induced E. M. F. is present all the time that the current is flowing, and this E. M. F. has a marked influence on the flow of the current. The induced E. M. F. tends to oppose any change in the current, thereby choking it back and making the circuit appear as if it had a

higher resistance than when a direct current was sent through it. In addition to the self-induction increasing the apparent resistance of the circuit, it makes it behave as if it possessed inertia, and the current does not respond at once to the changes in the applied E. M. F., but lags behind it, thus throwing the current and E. M. F. out of phase. The effects of capacity are exactly the opposite to those of self-induction, as will be shown later.

40. In dealing with alternating-current problems that arise in practice, we have the following classes of circuits to consider: Circuits containing resistance only, circuits containing self-induction only, circuits containing resistance and self-induction, circuits containing capacity only, circuits containing resistance and capacity, circuits containing self-induction and capacity, and circuits containing resistance, self-induction and capacity.

CIRCUITS CONTAINING RESISTANCE ONLY

41. It is possible to have an alternating-current circuit or device that possesses no self-induction, or at least where the self-induction is so small as to be almost negligible. If coils are wound by first doubling the wire on itself, as explained in connection with resistance boxes, they have practically no self-induction, because the magnetizing action of one-half of the turns is neutralized by that of the other half; a water rheostat or a load of incandescent lamps has very little self-induction. Such devices constitute a **non-inductive load.**

42. If an alternating E. M. F. E is applied to a non-inductive resistance R, the current set up through the resistance will be $I = \frac{E}{R}$, because there is no induced E. M. F. present to choke back the current, and the only thing that opposes the flow of the current is the ohmic resistance R. By the ohmic resistance is here meant that resistance which the circuit offers on account of its inherent

properties as a conductor, i. e., the resistance that depends on the length, cross-section, and material of the conductor. Also, since $E = IR$, it follows, since the value of R is fixed, that when E is at its maximum value, I must also be at its maximum value, and when E is passing through zero, I is also passing through zero. From the foregoing, then, we may state that:

When an alternating E. M. F. is applied to a non-inductive circuit, the current flows in accordance with Ohm's law, $I = \frac{E}{R}$, *and, hence, is of the same amount as if a direct E. M. F. of like value were applied to the circuit.*

When an alternating current flows through a non-inductive circuit, the current is in phase with the applied E. M. F.

EXAMPLE.—An alternating E. M. F. of 300 volts is applied to a load of lamps having a combined resistance of 2 ohms. (*a*) What current will flow in the circuit? (*b*) What will be the phase difference between the current and E. M. F.?

SOLUTION.—(*a*) Since the resistance is non-inductive, the current will flow according to Ohm's law and will be $\frac{300}{2} = 150$ amperes. Ans.

(*b*) The current will be in phase with the E. M. F.; hence, the angle of phase difference will be 0°. Ans.

CIRCUITS CONTAINING SELF-INDUCTION ONLY

43. In practice, it is, of course, impossible to obtain any device or electrical circuit that is entirely devoid of resistance, so that when we speak of a circuit that contains self-induction only, it is understood to be one in which the opposition to the current on account of the resistance is negligible compared with that of the induced E. M. F. If the circuit has a negligible resistance, it is evident that the E. M. F. applied or impressed on the circuit is taken up wholly in overcoming the induced E. M. F.; hence, the impressed E. M. F. must be the equal and opposite to that induced in the coil. Of course, the only E. M. F. that is actually present is that impressed on the circuit, but in working alternating-current problems it makes matters

clearer to imagine the impressed E. M. F. as opposed by counter E. M. F.'s, due to the resistance or inductance, as the case may be. It has already been mentioned that when an alternating E. M. F. is applied to an inductive circuit, the current does not respond at once to the changes in the E. M. F., but lags behind it, because of the opposition that the self-induction offers to any change in the current.

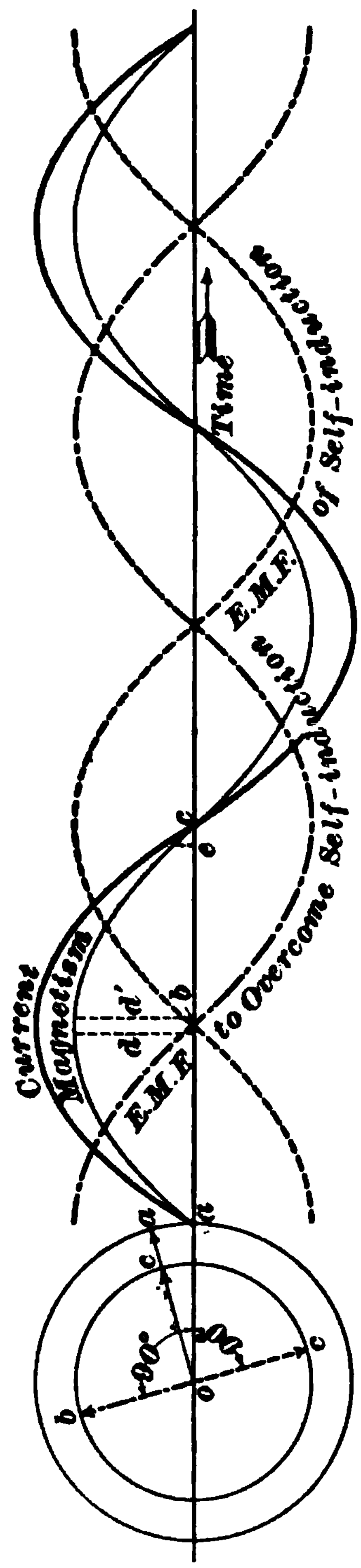


FIG. 26

The E. M. F. necessary to overcome self-induction is at right angles to the current and 90° ahead of the current in phase. This may be shown by referring to Fig. 26. Let the line *o a* and the corresponding wave shown by the full line represent the current flowing in the circuit. The magnetism produced by the current will increase and decrease in unison with it, and hence may be represented by the light-line wave in phase with the current. Now it has been shown that the induced E. M. F. is proportional to the rate at which the magnetism changes, and it will be seen from the figure that the magnetism is changing most rapidly at the points *a* and *c* where the magnetism curve cuts the axis, because there is a much greater change between two points such as *e* and *c* than there is between *d* and *d'*. It follows, then, that when the current and magnetism are passing through their zero values, the induced E. M. F. is at its maximum value; consequently, it must be at right angles to the current.

44. It is now necessary to determine whether this induced E. M. F. is 90° ahead of the current or behind it.

When the current is rising in the circuit, the induced E. M. F. is always preventing its rise; hence, it may be represented by the dotted curve, Fig. 26, 90° behind the current. By examining this curve, the student will see that the induced E. M. F. it represents opposes any change in the current. This induced E. M. F. may be represented by the line *o c*, 90° behind *o a*. The impressed E. M. F. necessary to overcome the self-induction will be the equal and opposite of this, and will be represented by the line *o b*, 90° ahead of *o a*. The E. M. F. to overcome the self-induction is also shown by the dot-and-dash curve. The student must keep in mind the distinction between the E. M. F. *of self-induction* and the E. M. F. *necessary to overcome self-induction;* the former is 90° behind the current in phase, while the latter is 90° ahead of the current.

45. In the foregoing, it has been assumed that the magnetism is exactly in phase with the current. This is not always the case where iron is present, as the hysteresis in the iron causes the magnetism to lag a little behind the current. It is true exactly for all circuits containing no iron, and sufficiently true, for most practical purposes, for iron circuits as well.

46. Value of Induced E. M. F.—The amount of the E. M. F. induced in any circuit or device depends on three things—the current, the frequency, and the coefficient of self-induction. The coefficient of self-induction L has already been explained; for any circuit or device without iron, it has a constant value regardless of the current. As already shown,

$$L = \frac{\Phi' T}{10^8}$$

where L = coefficient of self-induction expressed in henrys;
Φ' = number of magnetic lines set up by a current of 1 ampere;
T = number of turns through which the lines thread.

If the device contains iron in its magnetic circuit, as is nearly always the case, the value of L will change with the current. For example, the inductance of a coil wound on an iron core will change with the current, because with large currents the iron becomes saturated. If, however, the iron is worked well below the saturation limit, L will be fairly constant. From the above we have

$$L = \frac{\Phi T}{I \times 10^8} \qquad (2)$$

where Φ = flux corresponding to current I;

T = number of turns with which flux Φ is linked.

The effective value of the induced E. M. F. may be calculated as follows, when the inductance L is known: If the maximum magnetic flux is Φ, this total flux is cut four times by the coil during each cycle; i. e., the flux increases from zero to Φ, then decreases to zero, increases to Φ in the negative direction, and finally decreases to zero again. Now, by definition, the average volts induced in the coil must be equal to the average number of lines of force cut per second, divided by 10^8. If the coil has T turns and the frequency is n cycles per second, the average number of lines of force cut by all the turns per second will be $4 \Phi T n$, and the average volts induced will be

$$E \text{ av.} = \frac{4 \Phi T n}{10^8} \qquad (3)$$

or, since the effective volts is equal to 1.11 times the aver age volts,

$$\text{effective volts} = E = \frac{4.44 \Phi T n}{10^8} \qquad (4)$$

47. The formula giving the relation between the induced effective volts E, the frequency n, the number of turns T, and the flux Φ is important, as it is used repeatedly in connection with alternator, transformer, and induction-motor design. It may be expressed as follows: *Whenever a magnetic flux is made to vary through a circuit so as to induce a sine E. M. F., the effective value of the E. M. F. so induced*

is equal to 4.44 times the product of the maximum flux Φ, the number of turns T connected in series, and the frequency n divided by 10^8.

48. If the inductance of a circuit is L henrys, we have, from formula **2**,

$$\frac{\Phi\, T}{\mathbf{I} \times 10^8} = L,$$

where Φ is the maximum flux through the coil corresponding to the maximum current $\mathbf{I}$; L the inductance in henrys; and T the number of turns.

If I is the effective current flowing in the circuit, the maximum current must be $I\sqrt{2}$, because $I = \frac{1}{\sqrt{2}}\,\mathbf{I} = .707\ \mathbf{I}$.

Hence, $$\frac{\Phi\, T}{I\sqrt{2} \times 10^8} = L \qquad (5)$$

or $$\Phi\, T = I\sqrt{2}\, L\, 10^8 \qquad (6)$$

But from formula **4**, the effective E. M. F.,

$$E = \frac{4.44\ \Phi\, T n}{10^8} = \frac{4 \times \frac{.707}{.636}\ \Phi\, T n}{10^8} = 4 \times \frac{\frac{1}{\sqrt{2}}}{\frac{2}{\pi}} \times \frac{\Phi\, T n}{10^8}$$

NOTE.—In the above equation, the coefficient $4.44 = 4 \times 1.11 = 4 \times \frac{.707}{.636} = 4 \times \frac{\frac{1}{\sqrt{2}}}{\frac{2}{\pi}}$.

Substituting for $\Phi\, T$ the value given by formula **6**,

$$E = 4 \times \frac{\frac{1}{\sqrt{2}}}{\frac{2}{\pi}} \times n\, I\sqrt{2}\, L$$

$$E = 2\pi n L I \qquad (7)$$

This may be expressed as follows: *Whenever an alternating current of I amperes (effective) is sent through a circuit*

of inductance L henrys, the value of the induced E. M. F., in effective volts, is equal to 2 π times the product of the frequency n, the inductance L, and the effective current I.

In some works on alternating currents the quantity $2\pi n$ appearing in formula **7** is denoted by the Greek letter ω (omega), so that $2\pi n L$ is written ωL, and formula **7** reads $E = \omega L I$.

49. Reactance.—It will be seen from the foregoing that in order to obtain the volts necessary to overcome self-induction, the current is to be multiplied by the quantity $2\pi n L$. In order to obtain the E. M. F. necessary to overcome resistance, the current I is multiplied by the resistance R. It follows, then, that the quantity $2\pi n L$ is of the same nature as a resistance and is used in the same way as a resistance. The quantity $2\pi n L$ is called the **reactance** of the circuit, and, like resistance, is measured in ohms.

The reactance of any inductive circuit is equal to 2π times the frequency times the inductance L expressed in henrys.

Later on it will be seen that a more general definition of reactance as applied to any circuit is that it is the quantity that, multiplied by the current, gives the component of the impressed E. M. F. that is at right angles to the current.

50. Take the example shown in Fig. 27. The alternator A is connected to a coil or circuit $a\,b$, as shown, the

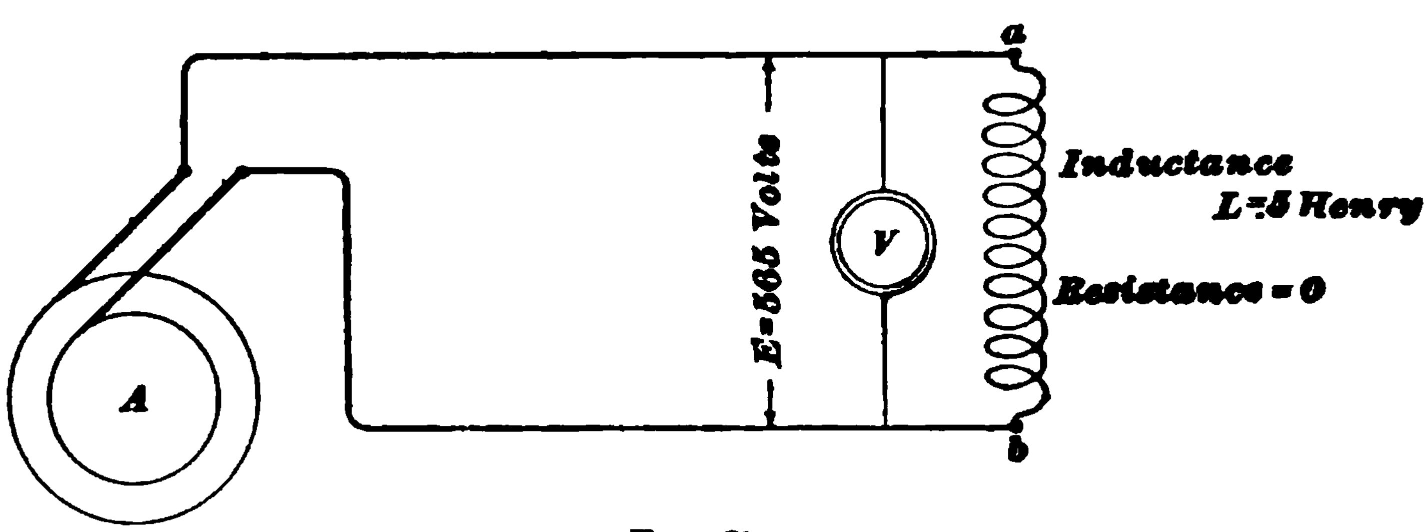


FIG. 27

inductance of which is .5 henry. The resistance of the circuit will be considered as negligible. The frequency of the E. M. F. furnished by the alternator is 60. Required, the

E. M. F. necessary to force a current of 3 amperes through the circuit. The induced counter E. M. F. will be

$$E = 2\pi n L I = 2\pi \times 60 \times .5 \times 3 = 565 \text{ volts}$$

Hence, in order to set up the current of 3 amperes, the alternator must furnish an E. M. F. of 565 volts. This example shows one difference between the behavior of alternating currents and direct currents. The E. M. F. required to set up a continuous current of 3 amperes through a circuit of very small resistance, such as this, would be exceedingly small, whereas it requires an alternating E. M. F. of 565 volts to set up the same current. In other words, if a continuous pressure of 565 volts were applied to the coil, the resulting current would be enormous. Instances of this effect are met with very commonly in connection with transformers. The primary coil of a transformer has a high self-inductance when the secondary is not loaded, so that, when the primary is connected to the alternating-current mains, only a very small current flows. If the same transformer were connected to continuous-current mains, it would be at once burned out, on account of the large current that would flow.

51. In the above example, the circuit was supposed to have negligible resistance, so that the whole of the applied E. M. F., 565 volts, was used to overcome the self-induction. This being the case, it follows that the E. M. F. applied by the alternator must be 90° ahead of the current. The state of affairs existing in the circuit may therefore be represented as in Fig. 28. Lay off to scale the value of the current $o\,a$ (so many amperes per inch) in the direction of the line $o\,x$. The induced E. M. F. $= 2\pi n L I =$ 565 volts must then be represented by the line $o\,b'$ (so many volts per inch) 90° behind $o\,a$, and the equal and opposite of this $o\,b$, 90° ahead of $o\,a$, will represent the E. M. F. that the alternator must supply to overcome the E. M. F. of self-induction. Of course, in actual practice it is impossible to obtain a circuit that has no resistance, as assumed in the above example; but if the reactance $2\pi n L$ is very large as

compared with the resistance, a condition quite frequently met with, the effect obtained in the circuit will be quite

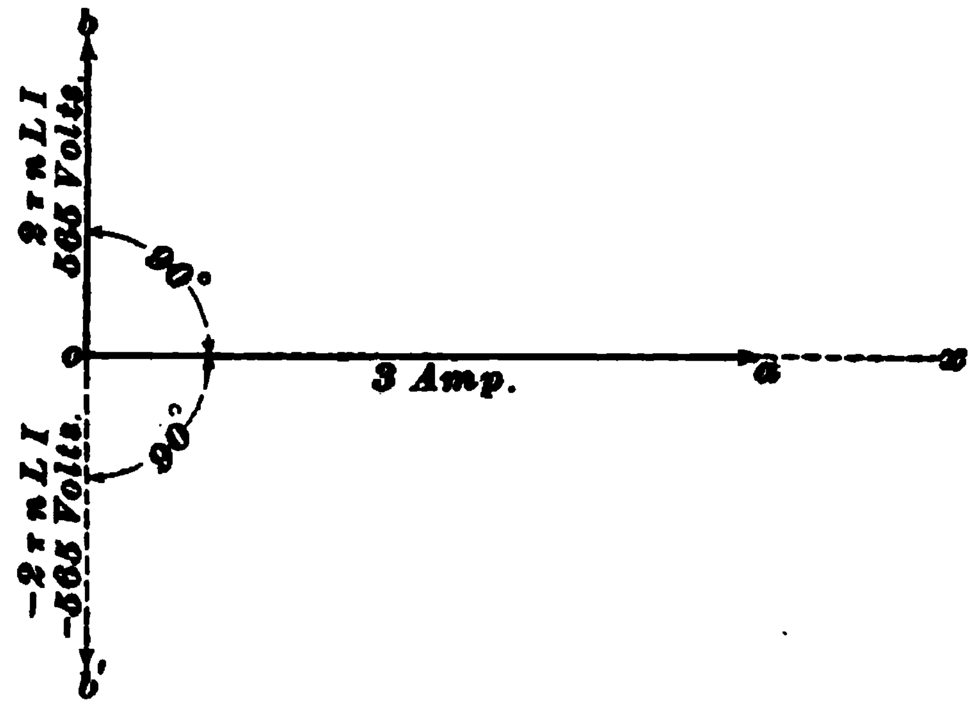


FIG. 28

closely represented by Fig. 28, and the current and E. M. F. will be nearly at right angles to each other.

CIRCUITS CONTAINING RESISTANCE AND SELF-INDUCTION

52. Components of Applied E. M. F.—It has been shown that the effect of self-induction is to choke back the current. It also makes the circuit act as if it possessed inertia, as the current does not respond at once to the changes in the applied E. M. F., and thus lags behind. The resistance of the coil also tends to prevent the current from flowing, but it does not tend to displace the current and E. M. F. in their phase relations. In considering the flow of current through circuits containing resistance and self-induction, it is convenient to think of the resistance and self-induction as setting up counter E. M. F.'s, which are opposed to the E. M. F. supplied by the alternator. The E. M. F. supplied from the alternator or other source must then, in the case of alternating-current circuits, overcome not only the resistance, but also the self-induction. In the case of continuous-current circuits, the resistance only must be taken into account. In every case, then, where an impressed E. M. F. encounters both resistance

and self-induction in a circuit, it may be looked on as split up into two components, one of which is necessary to overcome the resistance and the other the self-induction.

Take, for example, the case shown in Fig. 29. The alternator A is supplying an E. M. F. E. that is setting

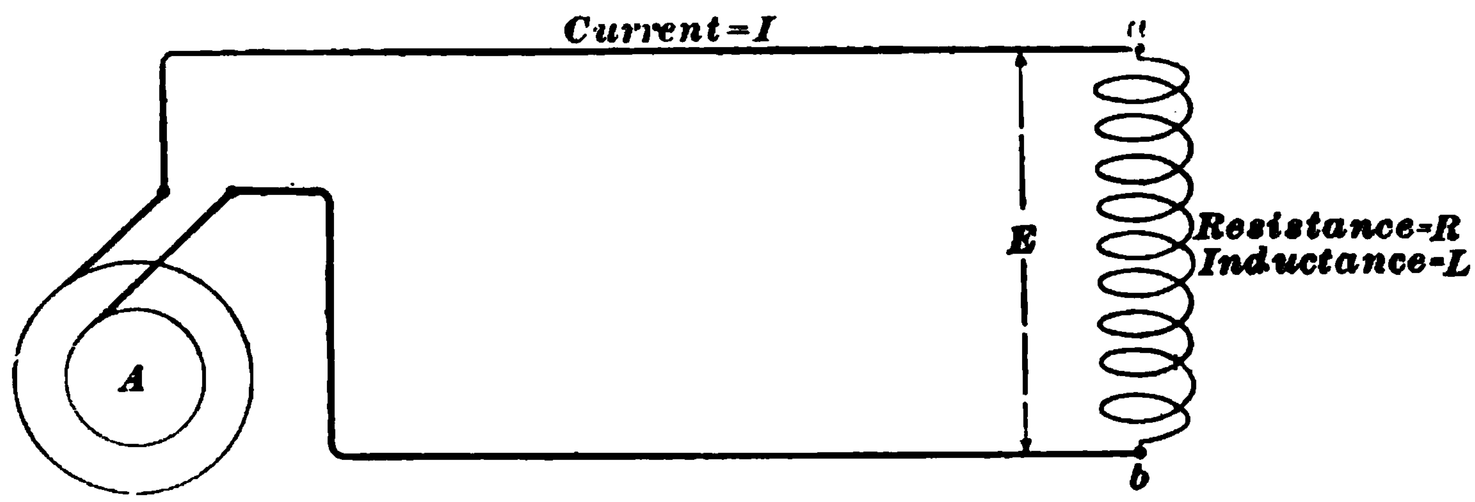


FIG. 29

up a current I through the circuit $a\,b$. This circuit possesses both resistance R (ohms) and inductance L (henrys). In such a circuit it might be desired to find the impressed E. M. F. necessary to set up a given current; or, given the impressed E. M. F., to find the current. Suppose it is required to find the impressed E. M. F. E necessary to set up a given current I. The E. M. F. required must be the

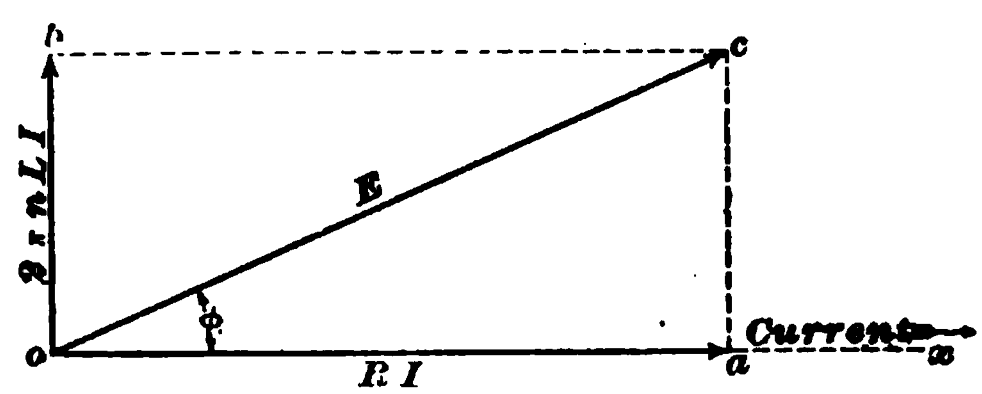


FIG. 30

resultant sum of the E. M. F. necessary to overcome the resistance and that required to overcome the self-induction. The former must be equal to $R\,I$, and must also be in phase with the current, while the latter is equal to the product of the current and reactance $2\,\pi\,n\,L\,I$ and must be 90° ahead of the current. In Fig. 30, $o\,a$ is therefore laid off to represent $R\,I$ in the same direction as the current, and $o\,b$, 90° ahead of the current, is laid off equal to $2\,\pi\,n\,L\,I$. The impressed E. M. F. E must be the resultant of $o\,a$ and $o\,b$,

or the diagonal oc, the electromotive forces being combined according to the parallelogram of forces, as previously explained. The diagonal oc therefore represents the E. M. F. set up by the alternator to the same scale that oa and ob represent the component E. M. F.'s. The diagram also shows that the current lags behind the impressed E. M. F. by the angle ϕ, and it is also seen that if the circuit had no inductance, the line ob would become zero, and the current would be in phase with the E. M. F.

53. Instead of using a complete parallelogram, as in Fig. 30, triangles are commonly used to show the relations

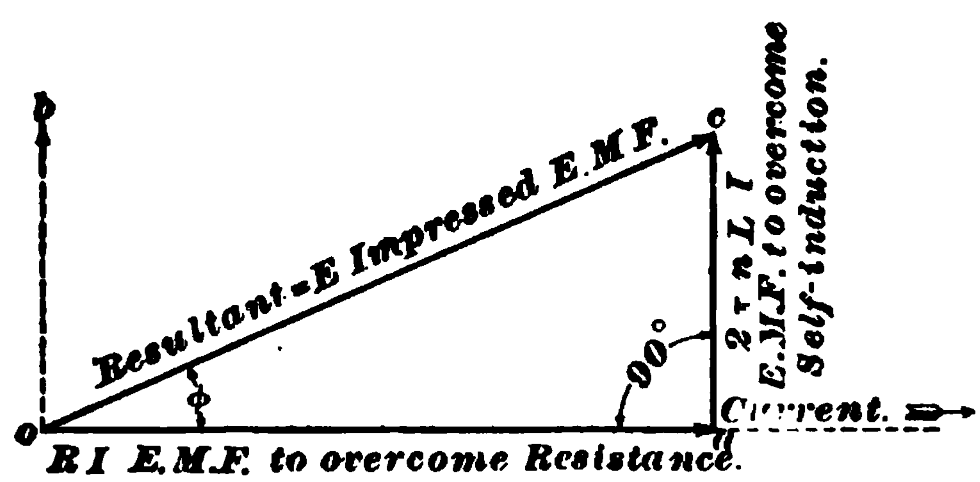


FIG. 31

between the different E. M. F.'s. The right triangle, Fig. 31, shows the same relations as the parallelogram, Fig. 30; $oa = RI$ represents the E. M. F. necessary to overcome resistance, ac that to overcome self-induction, and oc is the resultant. It should be remembered that the line ac is transferred from ob, and consequently represents an E. M. F. 90° ahead of oa. Since the angle oac is a right angle, it follows that

$$E^2 = R^2 I^2 + 4 \pi^2 n^2 L^2 I^2 \qquad (8)$$

or

$$E = \sqrt{R^2 I^2 + 4 \pi^2 n^2 L^2 I^2} \qquad (9)$$

$$= I \sqrt{R^2 + 4 \pi^2 n^2 L^2}$$

or

$$E = I \sqrt{R^2 + (2 \pi n L)^2} \qquad (10)$$

That is, the impressed E. M. F. E necessary to maintain a current I in a circuit of resistance R and inductance L is equal to the product of the current I into the square root of the sum of the squares of the resistance R and the reactance $2 \pi n L$.

The quantity $\sqrt{R^2 + (2\pi n L)^2}$ is called the *impedance* of the circuit. The impedance of a circuit is equal to the square root of the sum of the squares of the resistance and reactance.

54. The relation between resistance, reactance, and impedance is shown by the right-angled triangle, Fig. 32. The following definitions may also be given of impedance, reactance, and resistance:

Impedance is that quantity which multiplied by the current gives the impressed E. M. F.

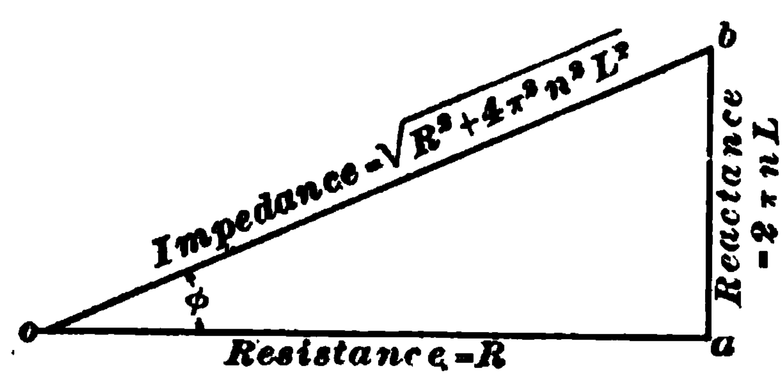


FIG. 32

Reactance is that quantity which multiplied by the current gives the component of the impressed E. M. F. that is at right angles to the current.

Resistance is that quantity which multiplied by the current gives the component of the impressed E. M. F. that is in phase with the current.

Impedances, like resistances and reactances, are expressed in ohms.

55. In dealing with continuous-current systems, the relation between the current, resistance, and E. M. F. is fully given by Ohm's law, i. e., current $= \frac{\text{E. M. F.}}{\text{resistance}}$. Ohm's law cannot, however, be applied in this form to alternating-current circuits, but from formula **10** becomes

$$I = \frac{E}{\sqrt{R^2 + (2\pi n L)^2}} \qquad \textbf{(11)}$$

or

$$\text{current} = \frac{\text{E. M. F.}}{\text{impedance}}$$

and the current no longer depends simply on the E. M. F. and resistance, but depends also on the inductance L and the frequency n. If n becomes zero, i. e., if the alternations become slower and slower until the current finally becomes continuous, the term $(2\pi n L)^2$ drops out and

formula **11** reduces to $I = \frac{E}{\sqrt{R^2}}$ or $I = \frac{E}{R}$. Also, if the circuit is non-inductive, i. e., if $L = 0$, the formula reduces to Ohm's law, and the current may be obtained by simply dividing the E. M. F. by the resistance, as is the case with continuous currents.

ANGLE OF LAG

56. From the triangle, Fig. 32, it will be seen that the current that is in the direction of $o\,a$ lags behind the impressed E. M. F., in the direction of $o\,b$, by the angle ϕ. The tangent of this angle ϕ is equal to $\frac{2\,\pi\,n\,L}{R}$; hence, if the resistance, reactance, and frequency are known, the angle of lag can be calculated. From the relation $\tan \phi = \frac{2\,\pi\,n\,L}{R}$, it is seen that the larger $2\,\pi\,n\,L$ is, compared with R, the larger will be the angle of lag, and if the reactance $2\,\pi\,n\,L$ is small in comparison with R, the angle ϕ will be small, or the current will be nearly in phase with the impressed E. M. F.; hence, in a circuit containing resistance and self-induction, the current lags behind the impressed E. M. F., the amount of the lag depending on the relative magnitude of the resistance and reactance.

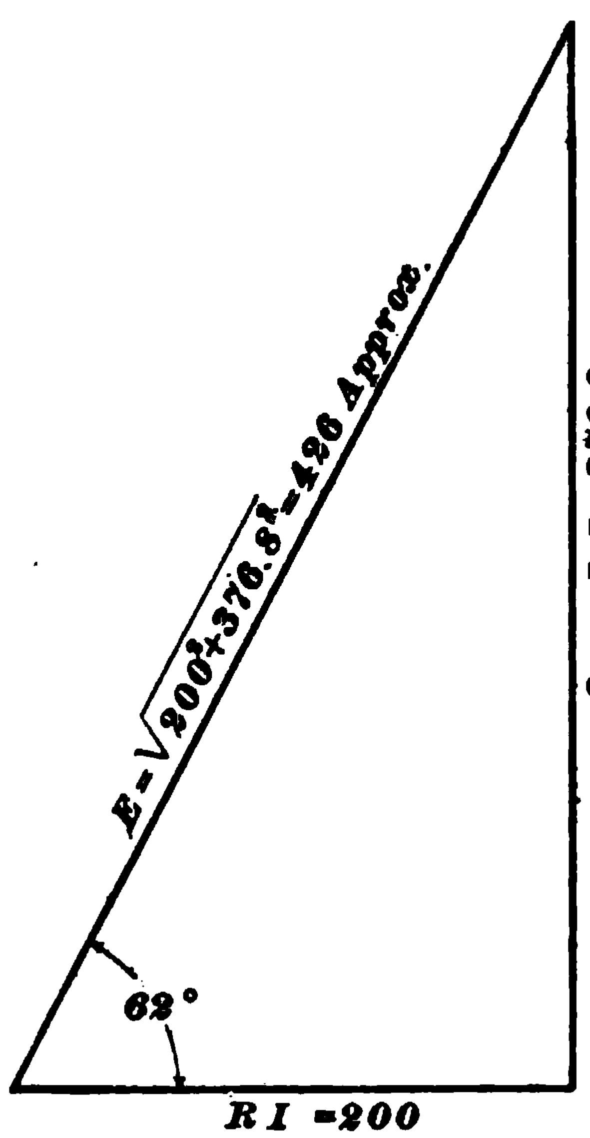


FIG. 33

EXAMPLE.—An alternator is connected to a circuit having a resistance of 20 ohms and an inductance of .1 henry. The frequency is 60 cycles per second. What must be the E. M. F. furnished by the alternator in order to set up a current of 10 amperes in the circuit?

SOLUTION.—The required E. M. F. must be the resultant of the E. M. F. necessary to overcome resistance, i. e., $R\,I = 20 \times 10 = 200$ volts, and that necessary to overcome the self-induction. The latter is equal to the reactance multiplied by the current, or $2\,\pi\,n\,L\,I = 2 \times 3.14 \times 60 \times .1$

$\times 10 = 376.8$ volts. The impressed E. M. F. E is the resultant, or $E = \sqrt{200^2 + 376.8^2} = 426.5$, nearly. These E. M. F.'s are related as shown in Fig. 33, and the resultant E may either be found by calculation, as shown, or it may be scaled from the figure. The required E. M. F. that must be supplied by the alternator is therefore 426.5 volts.

The current in the circuit will lag behind the E. M. F. by an angle ϕ, the tangent of which is $\frac{2 \pi n L}{R} = 1.88$. By looking up the angle in a table of tangents, it is found to be a little over 62°. This means, then, that in this particular circuit the current does not come to its maximum value until a little over $\frac{1}{6}$ period behind the E. M. F. Since the current passes through 60 cycles per second, it follows that the current in this case rises to its maximum value about $\frac{1}{360}$ second after the E. M. F.

The impedance of the circuit is $\sqrt{20^2 + 37.68^2} = 42.65$ ohms, and this multiplied by the current gives 426.5 volts as the impressed E. M. F. Ans.

57. The foregoing problem might also come up in another form: The impressed E. M. F. being given, to determine the current. From formula **11,**

$$I = \frac{E}{\sqrt{R^2 + (2 \pi n L)^2}}$$

so that, if E is given, I can easily be determined, R and L being known quantities.

If there were no inductance in the circuit, the E. M. F. required would be in accordance with Ohm's law, or $20 \times 10 = 200$ volts, which is less than half the voltage required when the inductance is present.

If there were no resistance present, the tangent of the angle of lag would be $\frac{2 \pi n L}{0} = \infty$, or the angle of lag would be 90°, all the impressed E. M. F. being used in overcoming the inductance.

CIRCUITS CONTAINING CAPACITY ONLY

58. If an electrical condenser be connected across the terminals of an alternator, we have an example of a circuit of large capacity, and as the resistance of the connecting wires is very short, the resistance of the circuit outside of the condenser itself is practically zero. We then have a circuit that may be considered as containing capacity only.

59. Condenser Charges.—If a battery be connected to the terminals of a condenser, as shown in Fig. 34, a current will flow into it and the plates will become charged. The flow of current will be a maximum the instant the E. M. F. is applied, but will rapidly fall off, so that in a small fraction of a second the current will practically have ceased flowing and the condenser will be charged. This will be the state of affairs so long as the condenser remains connected to the battery; except for the instant when the battery is first connected, no current will flow, and the circuit will act simply as if it were broken. The condenser acts as if it had acquired a counter E. M. F., tending to keep out the current, and this counter E. M. F. becomes greater until, when the condenser is charged, it is equal and opposite to that of the battery. If the battery be disconnected and the terminals of the condenser connected together, the charge will flow out and will result in a current of short duration. This current will be a maximum when the terminals are first connected, but it soon falls to zero. The unit of capacity is the *farad*, which has already been defined. For convenience, the *microfarad* is used as the practical unit, but in working out problems, capacities must always be expressed in farads before substituting in formulas, because the farad is chosen with respect to the volt and ampere, and hence must be used in formulas together with these units. For example, a capacity of 10 microfarads as given in a problem would be substituted in formulas as .00001 farad.

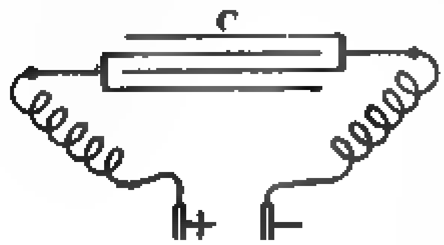


FIG. 34

60. In connection with condensers and capacities, it is often necessary to make use of the unit denoting quantity of charge. The unit of quantity is the *coulomb*, which has already been defined. It will be convenient to repeat here some of the definitions given, in order to assist in a thorough comprehension of that which follows. The coulomb represents that

quantity of current that passes through a circuit when the average rate of flow is 1 ampere for 1 second. If Q = quantity of electricity, or charge, in coulombs that a condenser takes up in t seconds, the average current during the time t must have been

$$I = \frac{Q}{t} \qquad (12)$$

61. If a condenser C, Fig. 35, be connected to an alternator, a current will flow into and out of it, because the E. M. F. at its terminals is constantly changing. If an

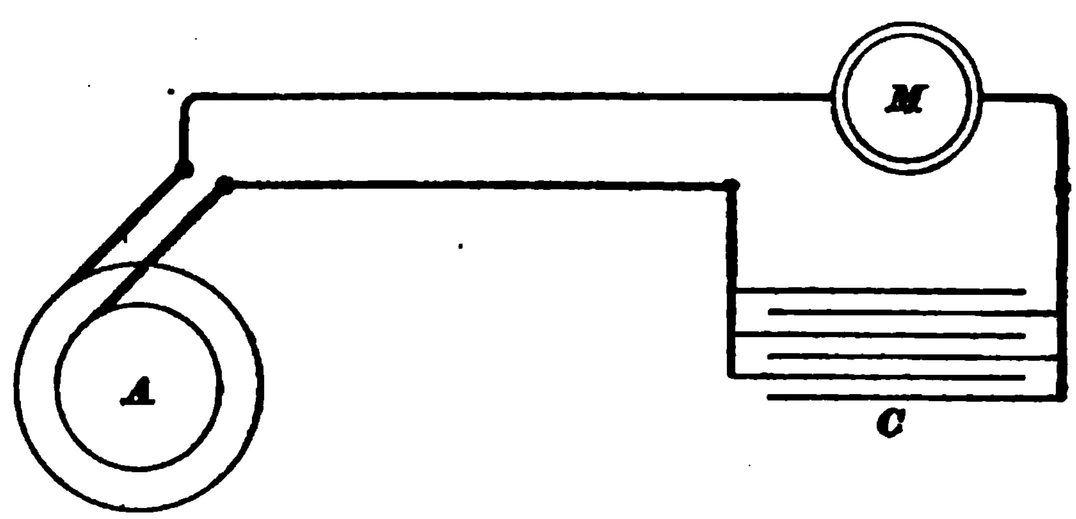


FIG. 35

ammeter M is connected in the circuit, it will give a reading just as if the alternator were sending a current through an ordinary circuit, whereas there is really no electrical connection between the terminals of the condenser C, and if it were connected to a continuous-current dynamo, the ammeter M would give no reading whatever. What really occurs is a surging of current into and out of the condenser.

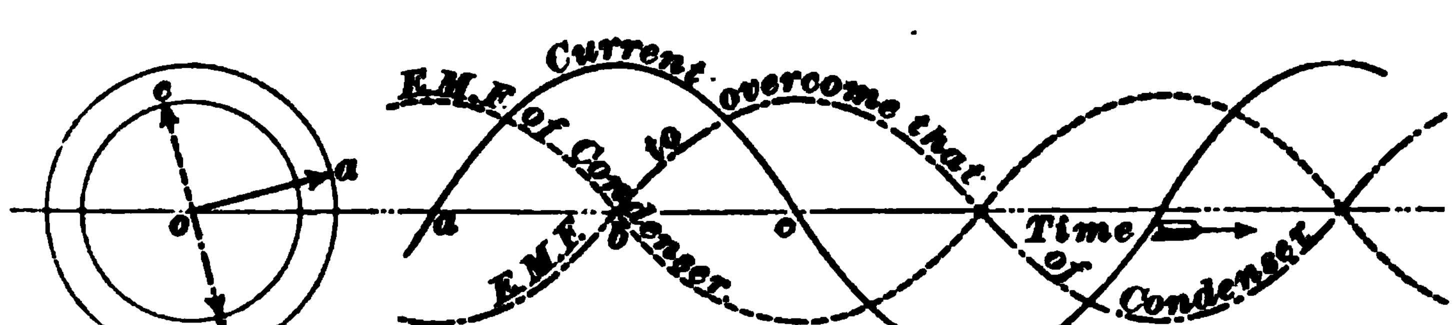


FIG. 36

62. Condenser E. M. F.—Let the full-line curve, Fig. 36, represent the current that flows into and out of a condenser when a sine E. M. F. is impressed on its terminals. This current will, of course, have a frequency equal to that of the

alternator to which the condenser is attached. It will require a certain impressed E. M. F. to cause this current to flow, just as it required an E. M. F. to overcome the inductance of a circuit. The problem now is to determine the value of this E. M. F. and its phase relation with regard to the current.

The E. M. F. required to set up the current will be the equal and opposite of the E. M. F. of the condenser, just as the E. M. F. to overcome self-induction was the equal and opposite of the E. M. F. of self-induction.

63. It has already been shown that when the flow of current into the condenser is a maximum the counter E. M. F. of the condenser is zero, and when the flow finally becomes zero the counter E. M. F. is a maximum. It follows, therefore, that the wave representing the E. M. F. of the condenser is at right angles to the current. The fact as to whether it is 90° ahead of or behind the current may be decided as follows: When the current is flowing into the condenser, the counter E. M. F. is continually increasing in such a direction as to keep it out. The curve representing the E. M. F. of the condenser must cross the axis at the point *b*, Fig. 36, because, as shown above, this curve is at right angles to the current curve. During the interval of time from *b* to *c*, the current is decreasing, so that during this interval the counter E. M. F. of the condenser must be increasing in the opposite direction, and is therefore represented by the dotted curve, which is 90° ahead of the current. The impressed E. M. F. necessary to overcome that of the condenser must be the equal and opposite of this, or 90° behind the current. This latter E. M. F. is shown by the dot-and-dash curve. The lines in the diagram at the left show these phase relations, the line *o a* representing the current, *o c* the E. M. F. of the condenser, and *o b* the impressed E. M. F. to overcome that of the condenser.

Hence, in a circuit containing capacity only, the current is 90° ahead of the impressed E. M. F., or the E. M. F. necessary to set up a current in such a circuit is 90° behind the current in phase.

In Fig. 37, the current is represented by the line $O a$ and the impressed E. M. F. necessary to maintain the current by $O b$, 90° behind $O a$. The counter E. M. F. of the condenser itself would be represented by $O c$, equal and opposite to $O b$, and hence 90° ahead of the current.

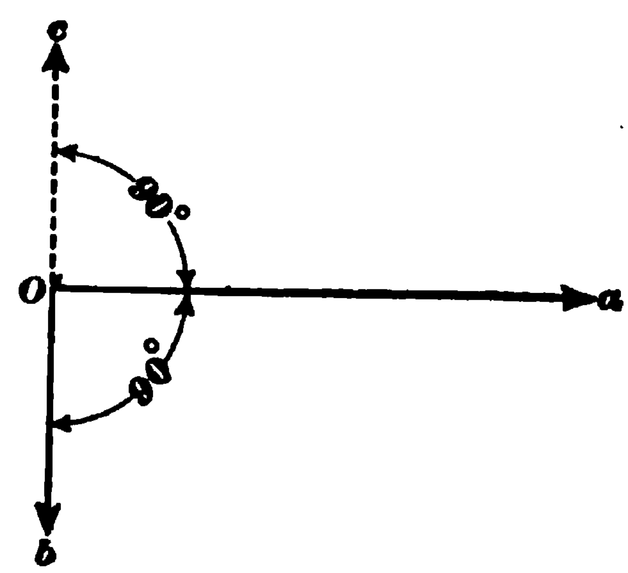


FIG. 37

64. The student will note from the foregoing that the effect of capacity in a circuit is exactly the opposite of self-induction. Capacity tends to make the current lead the E. M. F., while self-induction causes it to lag. When both self-induction and capacity are present in a circuit, one tends to neutralize the other.

65. The E. M. F. in volts (effective) necessary to overcome the capacity or condenser E. M. F. in a circuit may be calculated as follows:

If the capacity of the condenser be C farads and a maximum E. M. F. $\mathbf{E}$ be applied to its terminals, it will take up a maximum charge $Q = C\,\mathbf{E}$ coulombs. The E. M. F. passes through n cycles per second, i. e., the condenser is charged up to a maximum in one direction, then discharged, and the process repeated in the opposite direction, n times per second. The average rate of charge and discharge is, therefore, $4\,n$, i. e., $4\,n$ times per second.

The maximum rate $=$ average rate $\times \frac{\pi}{2}$; hence, the maximum rate of charge and discharge is $\frac{4\,n \times \pi}{2} = 2\,\pi\,n$. The maximum charge is $C\,\mathbf{E}$, and if the maximum rate of charge is $2\,\pi\,n$, the maximum current must be

$$\mathbf{I} = 2\,\pi\,n\,C\,\mathbf{E} \qquad (13)$$

Hence,
$$\mathbf{E} = \frac{\mathbf{I}}{2\,\pi\,n\,C} \qquad (14)$$

This formula gives the relation between the maximum E. M. F. and maximum current. The effective E. M. F. is

equal to the maximum divided by $\sqrt{2}$. Dividing each side of the equation by $\sqrt{2}$, we have

$$\frac{\mathsf{E}}{\sqrt{2}} = \frac{\mathsf{I}}{2\pi n C\sqrt{2}}; \text{ or, } E = I\frac{1}{2\pi n C} \qquad \textbf{(15)}$$

so it is seen that this equation also gives the relation between the effective E. M. F. and current.

66. Capacity Reactance.—The quantity $\frac{1}{2\pi n C}$ is called the **capacity reactance,** as it is analogous to the reactance $2\pi n L$ in circuits where self-induction is present. It has also been called the *condensance* by some writers.

EXAMPLE 1.—Required, the E. M. F. necessary to set up an alternating current of 2 amperes through a condenser having a capacity of 5 microfarads, the frequency being 60 cycles per second.

SOLUTION.—By formula **15,** we have

$$E = I\frac{1}{2\pi n C}$$

$I = 2$ amperes; $C = 5$ microfarads $= .000005$ farad; $n = 60$;

$$E = \frac{2}{2 \times 3.14 \times 60 \times .000005} = 1{,}061 \text{ volts} \quad \text{Ans.}$$

EXAMPLE 2.—$B\,B$, Fig. 38, represents a high-tension power-transmission line connected to an alternator A. The pressure maintained between the lines is 10,000 volts, and the frequency is 60 cycles per second.

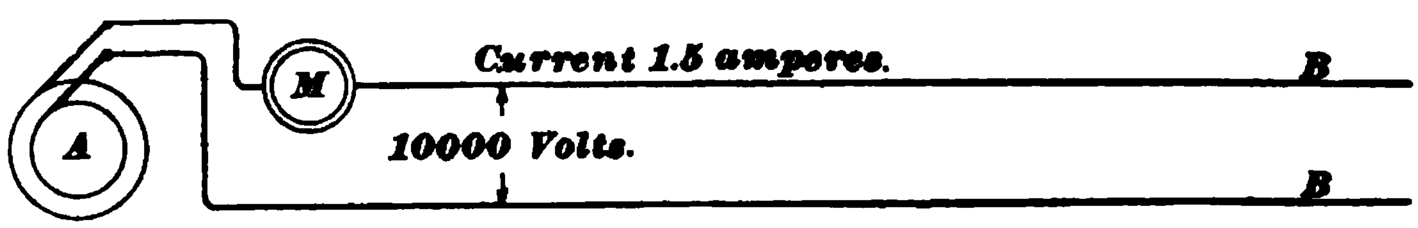


FIG. 38

There is no connection between the wires, and they are supposed to be so insulated that practically no leakage takes place between them. On running the alternator, it is found that the ammeter M gives a reading of 1.5 amperes. What must be the electrostatic capacity of the line?

SOLUTION.—From formula **15,** we have, by derivation,

$$I = 2\pi n C E,$$

$$C = \frac{I}{2\pi n E} = \frac{1.5}{2 \times 3.14 \times 60 \times 10{,}000} \text{ farads}$$

$$= \frac{1.5 \times 1{,}000{,}000}{2 \times 3.14 \times 60 \times 10{,}000} = .398 \text{ microfarad} \quad \text{Ans.}$$

ALTERNATING CURRENTS

(PART 2)

RESISTANCE, SELF-INDUCTION, AND CAPACITY

CIRCUITS CONTAINING RESISTANCE AND CAPACITY

1. In case a circuit contains resistance and capacity, the current will lead the E. M. F. The amount of lead will depend on the relative values of the resistance and capacity reactance. If the resistance is very large compared with the capacity reactance, the angle of lead will be small, because that component of the E. M. F. at right angles to the current will be small. On the other hand, if the capacity reactance is very large compared with the resistance, the current may lead the E. M. F. by nearly 90°.

2. The resultant E. M. F. may in such circuits be looked on as being composed of two components, one at right angles to the current, used in overcoming the capacity reactance and equal to $\frac{I}{2 \pi n C}$ and the other, necessary to overcome the resistance, equal to $R I$ and in phase with the current. These E. M. F.'s may be represented by the

diagram, Fig. 1. ox represents the current and $oa = RI$ the E. M. F. to overcome resistance. The E. M. F. to

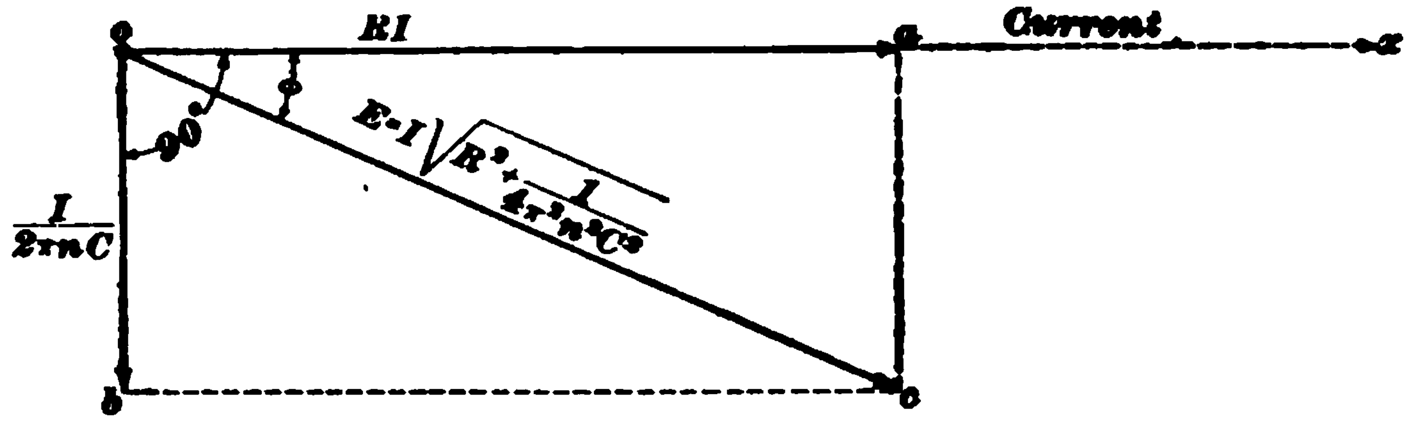


FIG. 1

overcome the capacity reactance is represented by ob 90° behind oa, and the resultant impressed E. M. F. E by the diagonal oc. The current leads the E. M. F. by the angle ϕ, the tangent of which is equal to $\frac{ac}{oa} = \frac{\frac{I}{2\pi n C}}{RI} = \frac{1}{2\pi n CR}$.

$$\tan \phi = \frac{1}{2\pi n CR} \qquad \textbf{(1)}$$

3. From formula **1** it will be noticed that if R becomes zero, $\tan \phi$ = infinity, or the angle of lead is 90°. If the capacity C becomes infinitely large, $\tan \phi = 0$ and the current is in phase with the E. M. F. This latter is the condition of affairs in an ordinary closed circuit, because in such a case the current keeps on flowing so long as the E. M. F. is applied, and the circuit never becomes charged. In other words, an ordinary closed circuit in which there is no condenser at all acts as if it had an infinitely large capacity, while an open circuit acts as a condenser of infinitely small capacity.

4. From the triangle oac, Fig. 1, we have the relation

$$E^2 = R^2 I^2 + \frac{I^2}{4\pi^2 n^2 C^2}$$

$$E = \sqrt{R^2 I^2 + \frac{I^2}{4\pi^2 n^2 C^2}} \qquad \textbf{(2)}$$

$$E = I\sqrt{R^2 + \left(\frac{1}{2\,\pi\,n\,C}\right)^2} \qquad (3)$$

Therefore, *in circuits containing resistance and capacity, the impedance of the circuit is equal to the square root of the sum of the squares of the resistance R and the capacity reactance* $\frac{1}{2\,\pi\,n\,C}$.

The law governing the flow of current in such a circuit then becomes

$$I = \frac{E}{\sqrt{R^2 + \frac{1}{4\,\pi^2\,n^2\,C^2}}} \qquad (4)$$

If the circuit contains a resistance R and no condenser, C becomes infinite in value, and formula 4 reduces to $I = \frac{E}{R}$. That is, the current follows Ohm's law.

If the circuit be broken, it means that the resistance becomes infinitely large, and the capacity C being very small, the impedance becomes infinitely large; consequently, the current becomes zero.

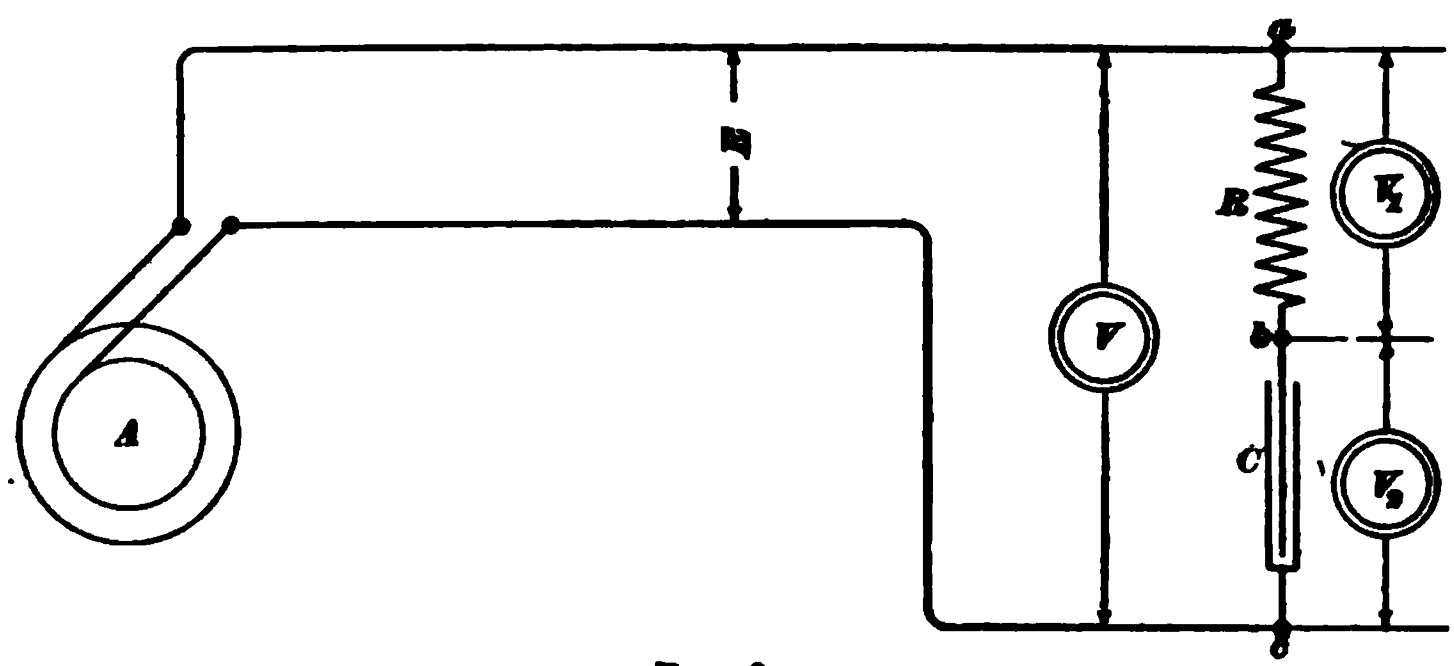


FIG. 2

EXAMPLE.—A non-inductive resistance R, Fig. 2, of 200 ohms is connected in series with a condenser across the terminals of an alternator, as shown, the frequency being 60. The condenser has a capacity

of 15 microfarads, and the current flowing in the circuit is 5 amperes. Required:

1. The reading that would be given by the voltmeter V_1 connected to the terminals of the resistance.

2. The reading of the voltmeter V_2 connected to the terminals of the condenser.

3. The angle by which the current will lead the E. M. F.

4. The E. M. F. that must be furnished by the alternator, i. e., the reading of the voltmeter V connected across the mains.

Solution.—We know that the three required E. M. F.'s must be related to each other as shown in Fig. 1.

1. The reading given by the voltmeter V_1 must evidently be the E. M. F. necessary to overcome the resistance R, and hence is equal to $R\,I = 200 \times 5 = 1{,}000$ volts. Ans.

2. The reading of V_2 represents the E. M. F. necessary to overcome the capacity reactance, and hence is equal to

$$\frac{I}{2\pi n C} = \frac{5}{2 \times 3.14 \times 60 \times .000015} = 884 \text{ volts} \quad \text{Ans.}$$

3. The angle by which the current leads the E. M. F. is given by formula 1; $\tan \phi = \frac{1}{2\pi n C R} = .884$. From a table of tangents ϕ is found to be 41° 29′, nearly; i. e., the current is ahead of the E. M. F. by a little more than one-ninth of a complete cycle. Ans.

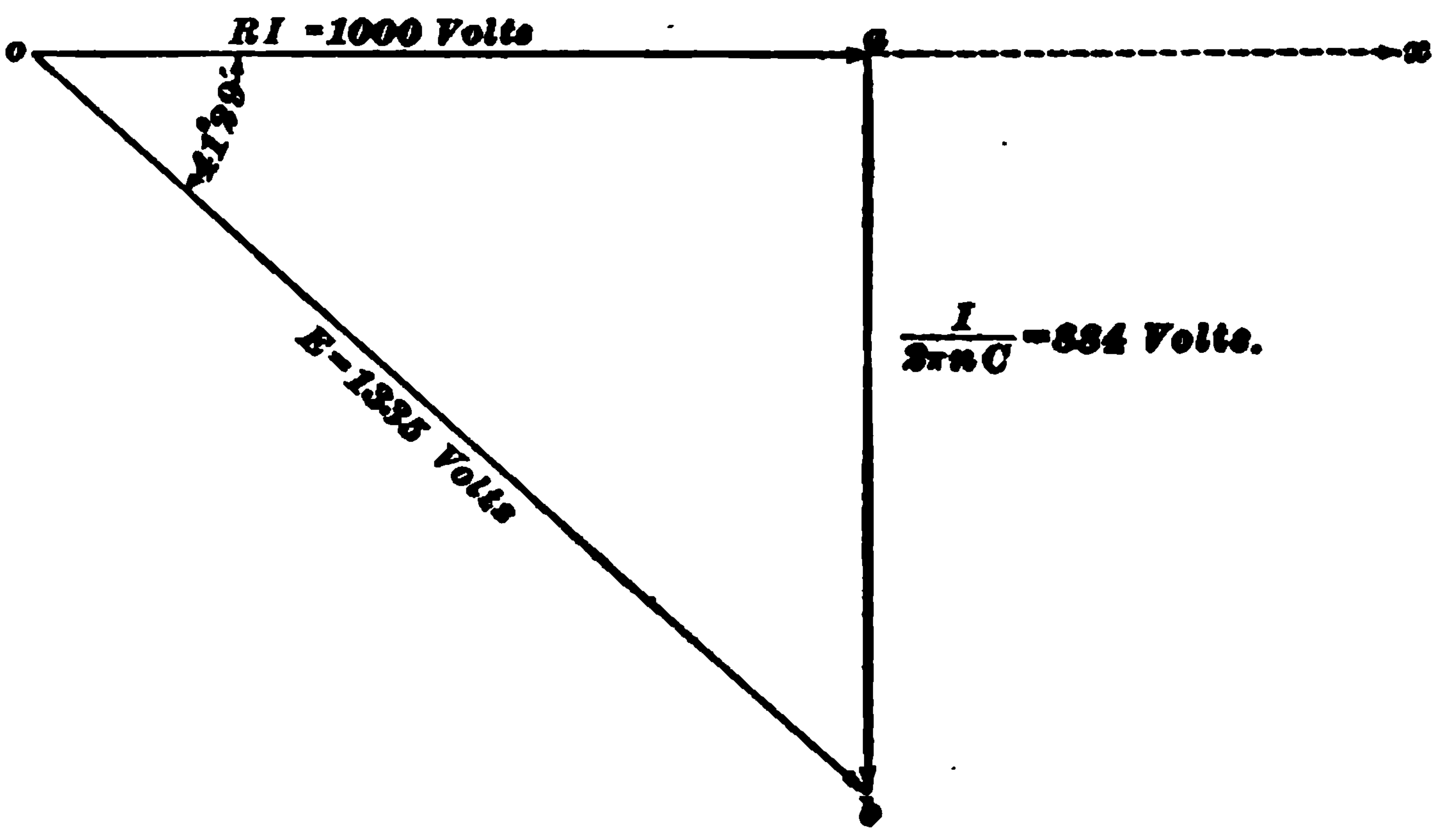


Fig. 3

4. The resultant E. M. F. E, or the voltage that must be furnished by the alternator to set up the current of 5 amperes, is obtained from

formula 2: $E = \sqrt{R^2 I^2 + \frac{I^2}{4 \pi^2 n^2 C^2}} = \sqrt{1{,}000^2 + 884^2} = 1{,}335$ volts.
This is the pressure that would be given by the voltmeter V, and it is the resultant sum of the E. M. F. to overcome resistance (1,000 volts) and that to overcome reactance (884 volts).

5. In an alternating-current circuit as considered in the above example, it is thus seen that it is quite possible for the reading of the voltmeter V to be considerably less than the arithmetical sum of V_1 and V_2.

The relation between the quantities in this problem is shown by the E. M. F. triangle, Fig. 3, the sides of the triangle being laid off to scale to represent the different E. M. F.'s.

6. Resistance and Capacity in Parallel.—An example of resistance and capacity connected in parallel is shown in Fig. 4. The alternator maintains a constant E. M. F. E across the terminals of both R and C. The current I that will flow in the main circuit under such conditions is determined as follows: Let the line $o\,a$, Fig. 5, represent the impressed E. M. F. E.

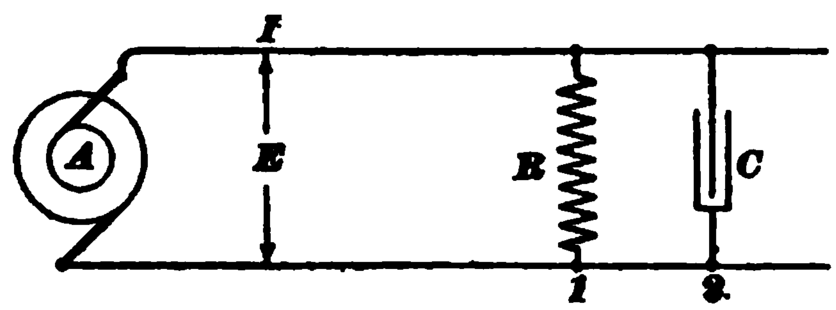


FIG. 4

R is a non-inductive resistance; hence, the current in branch *1* will be $I_1 = \frac{E}{R}$ and will be in phase with E; hence, it may be represented by a line such as $o\,b$.

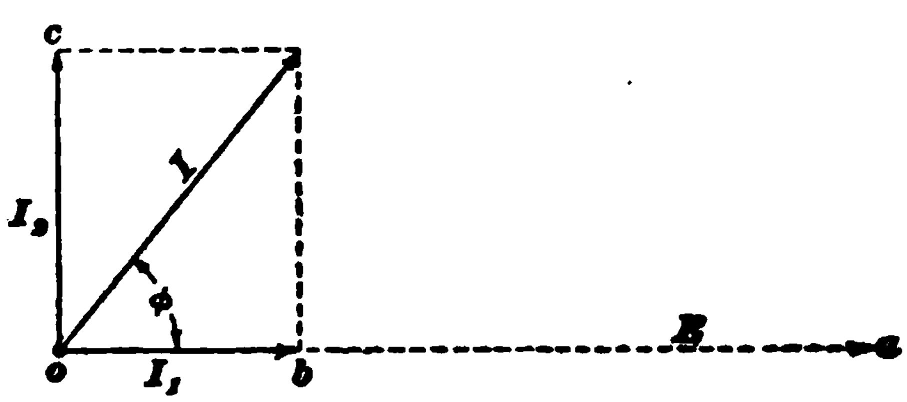


FIG. 5

The current in branch *2* is $I_2 = 2 \pi n C E$, and is 90° ahead of the E. M. F. in phase. The current in the line must be the resultant of I_1 and I_2, and is, therefore, represented by I, which leads the E. M. F. by the angle ϕ and is equal to $\sqrt{I_1^2 + I_2^2}$.

CIRCUITS CONTAINING SELF-INDUCTION AND CAPACITY

7. When a circuit contains self-induction and capacity, the two tend to neutralize each other, because it has already been shown that the effect of capacity is precisely the opposite to that of self-induction. Take the case shown in Fig. 6 where an inductance L and capacity C are connected in series across a circuit. Let I be the current that flows in the circuit. Then the E. M. F. E_1 across the inductance will be $2\pi n L I$, and will be 90° ahead of the current, or, in other words, the current will lag 90° behind the E. M. F. E_1. The E. M. F. E_2 across the capacity C must be $E_2 = \frac{I}{2\pi n C}$, and the current I must be 90° ahead of the E. M. F. E_2. This state of affairs may be represented as shown in Fig. 7; $o\,a$ represents the current I, and $o\,b$ the E. M. F. $E_1 = 2\pi n L I$, 90° ahead of the current; $o\,c$ is equal to $E_2 = \frac{I}{2\pi n C}$, and is 90° behind the current, or the current I is 90° ahead of the E. M. F. across the condenser. The line E. M. F. E is the difference between $o\,c$ and $o\,b$; it is, therefore, represented by $o\,d$, found by subtracting a length $dc = o\,b$ from $o\,c$. The line E. M. F. may be either ahead of or behind the current in phase, depending on the relative effects of the self-induction and capacity. It is easily seen that under the conditions shown in Fig. 7, the pressures E_1 and E_2 may

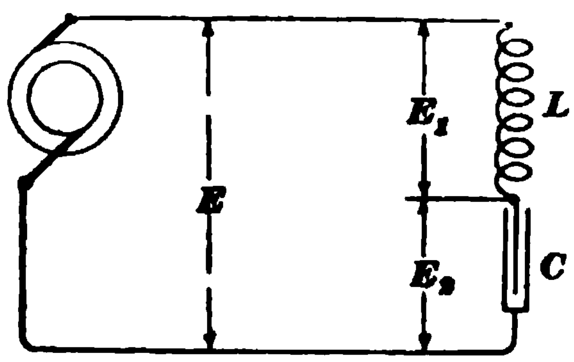


FIG. 6

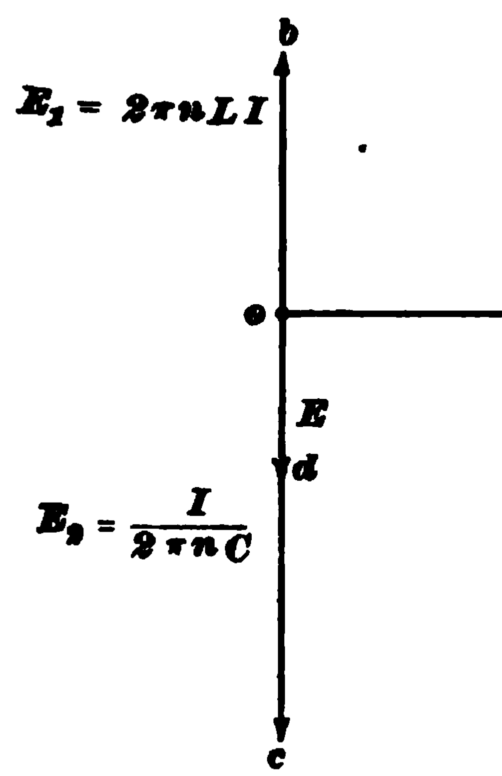


FIG. 7

be very much higher than the line pressure. It is, of course, impossible to get a circuit absolutely devoid of resistance, so that in practice *o b* and *o c* would not be exactly at right angles to *o a*. The conditions that would actually arise in practice would be more nearly represented by Fig. 8, where *o b* and *o c* are not exactly at right angles to *o a*, and where the resultant E. M. F. *o d* is found by completing the parallelogram *o b d c*.

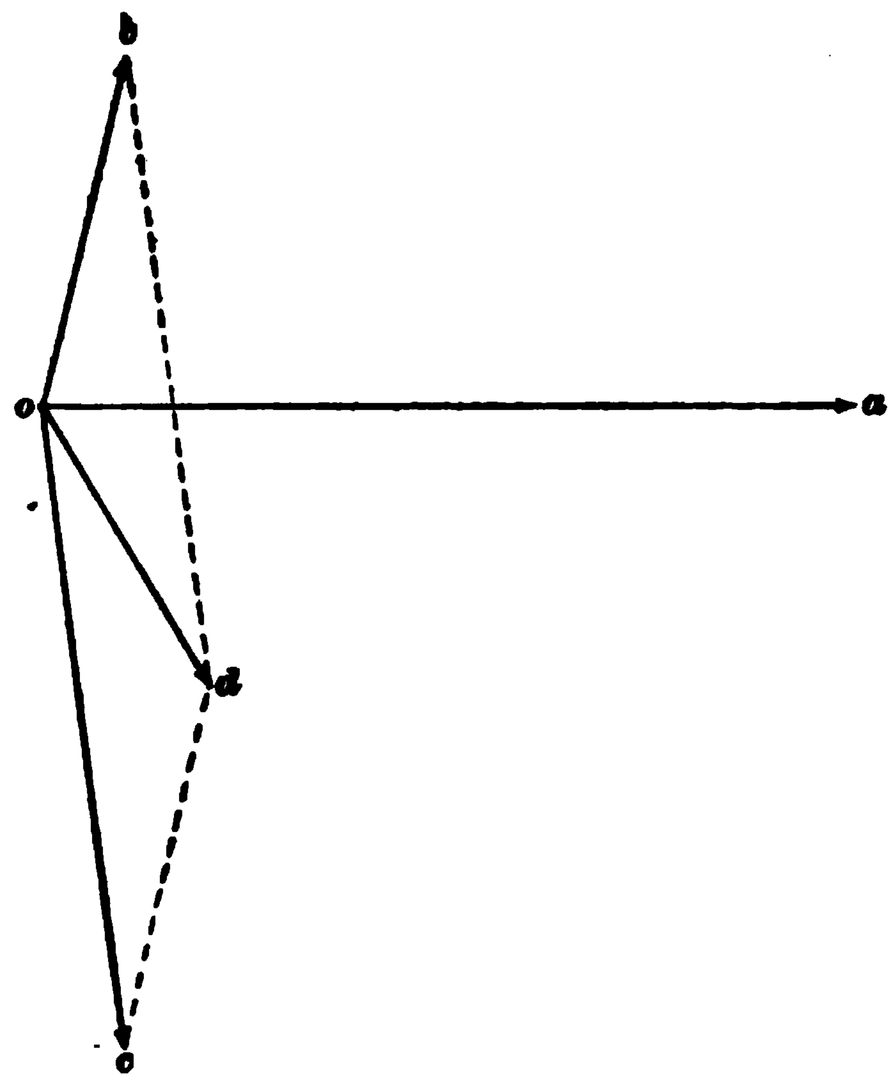


FIG. 8

8. **Self-Induction and Capacity in Parallel.**—Fig. 9 shows an inductance and capacity in parallel. In this case L, C, and E are known, and it is desired to find the value of I. The current in L would be $I_1 = \frac{E}{2\pi n L}$, since there is supposed to be no resistance present. The current in C would be $I_2 = 2\pi n C E$. I_1 is 90° behind the E. M. F., and I_2, 90° ahead of the E. M. F., so that the diagram for the circuit will be as shown in Fig. 10. *o a* represents the E. M. F. E; *o b* the current I_1, and *o c* the current I_2. The resultant current is I and shows that the current in the main line may be much less than the currents in the separate branches. If some resistance were present in each branch, I_1 and I_2 would not be

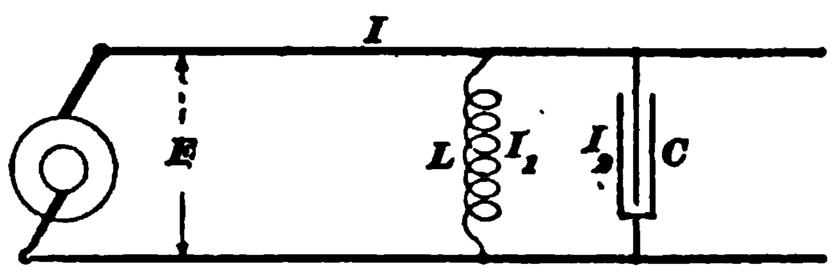


FIG. 9

exactly at right angles to E, and the diagram would be

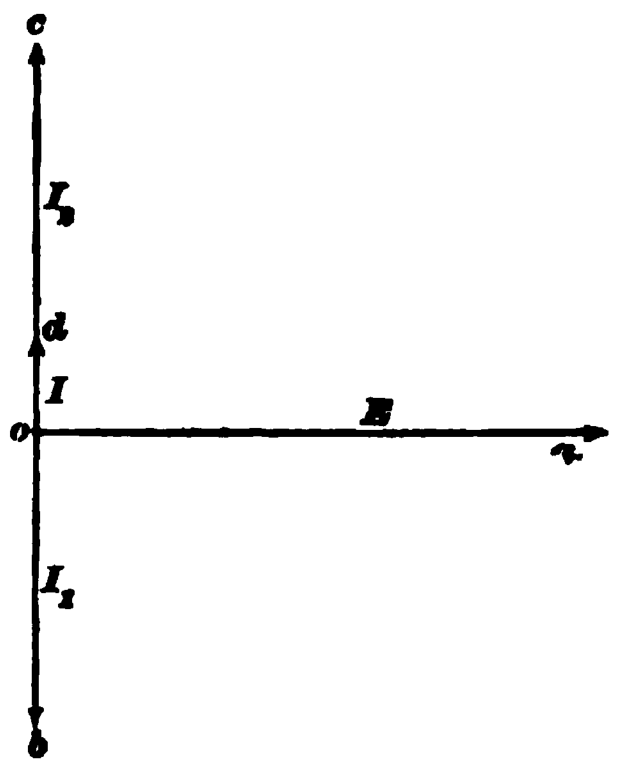


Fig. 10

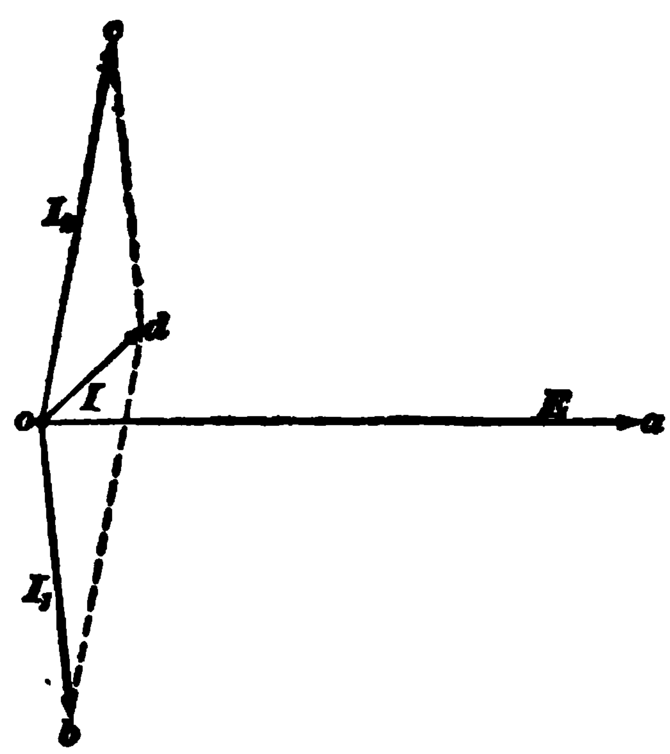


Fig. 11

as shown in Fig. 11, $o\,d = I$ being the current supplied by the alternator.

CIRCUITS CONTAINING RESISTANCE, SELF-INDUCTION, AND CAPACITY

9. Resistance, Self-Induction, and Capacity in Series. It quite frequently happens that a circuit may contain all three of these. The effect of all these three quantities—resistance, self-induction, and capacity—being present in a circuit is easily understood if it is remembered that self-induction and capacity always tend to neutralize each other. Suppose an alternator A, Fig. 12, is supplying current to the circuit $a\,b$ containing resistance R, inductance L, and capacity C, and suppose that the capacity reactance $\frac{1}{2\,\pi\,n\,C}$ is less than the reactance $2\,\pi\,n\,L$ due to the self-induction. The resultant E. M. F. E necessary to maintain the current in the circuit may then be determined as shown in Fig. 13. $o\,a$ represents, as in previous problems, the E. M. F. necessary to overcome the resistance $= R\,I$ and in phase with the

current along the line $o\,x$; $o\,c$, the E. M. F. to overcome self-induction, 90° ahead of $o\,a$, equal to $2\,\pi\,n\,L\,I$; and $o\,b$,

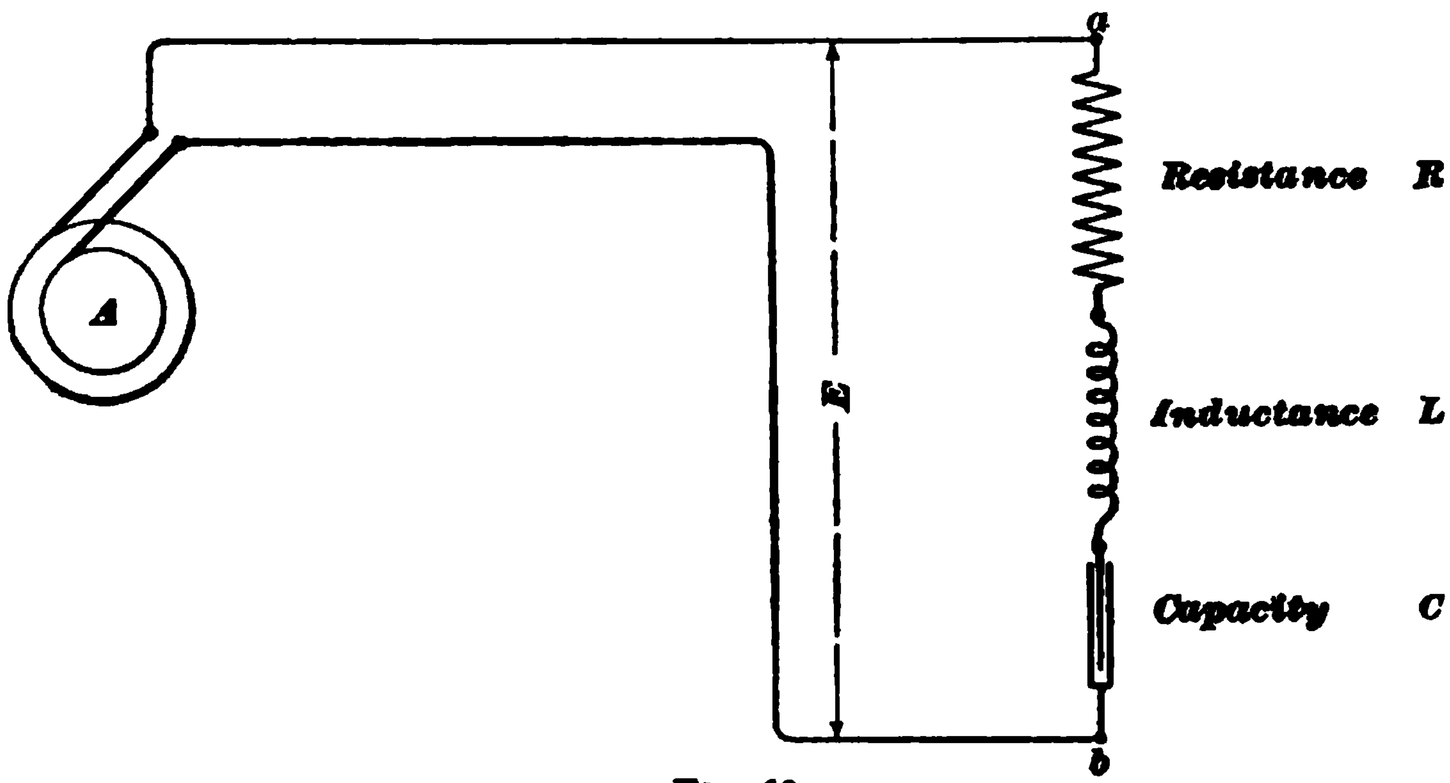


FIG. 12

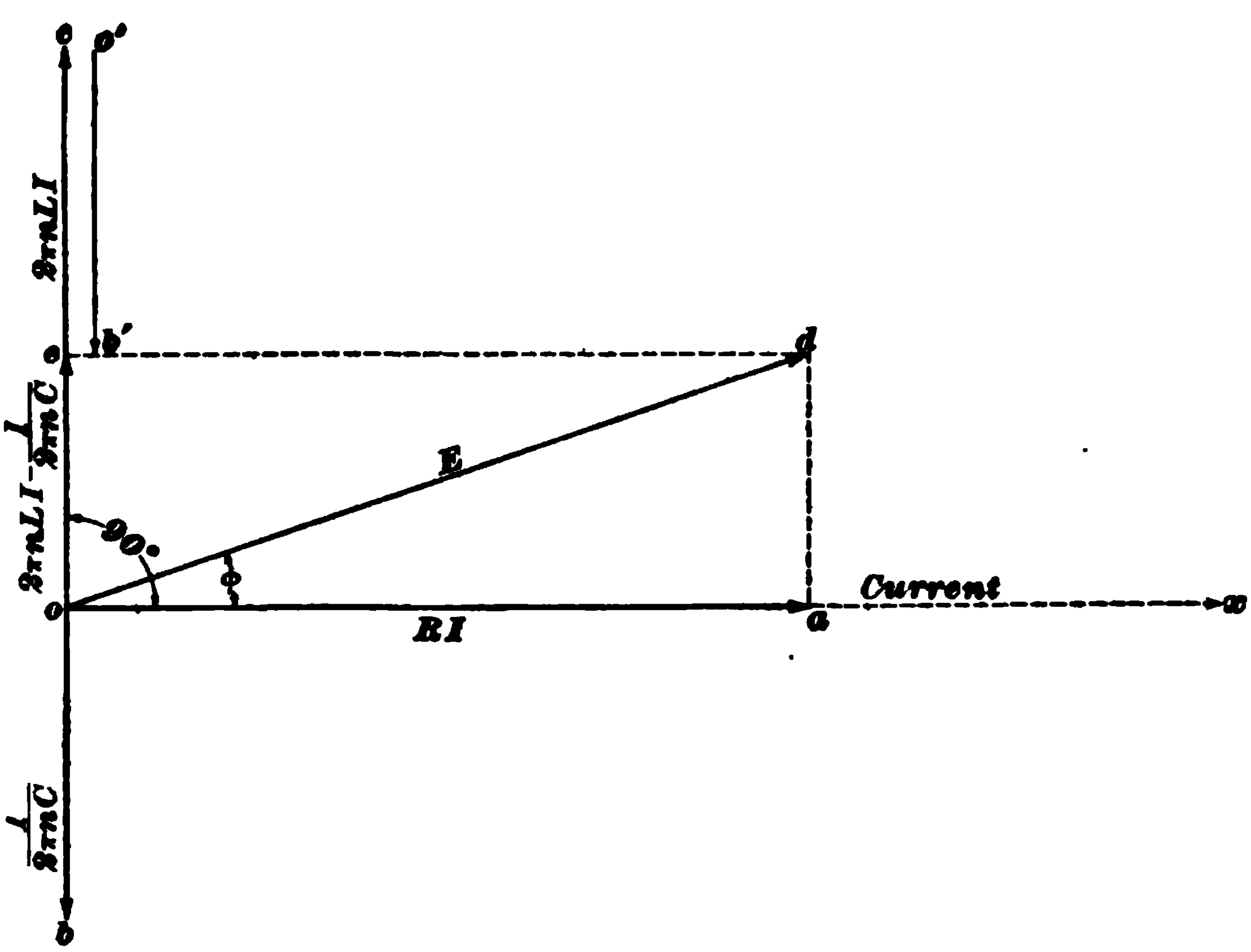


FIG. 13

the E. M. F. necessary to overcome capacity, 90° behind $o\,a$, equal to $\frac{I}{2\,\pi\,n\,C}$. The total component at right angles to

the current will be $2\pi n L I - \frac{I}{2\pi n C}$, and may be laid off by measuring back from c, $o'b' = ob$. oe is then the resultant component at right angles to the current, and the impressed E. M. F. furnished by the alternator is the resultant of oe and oa, i. e., the diagonal od. This resultant E. M. F. is in this case ahead of the current by the angle ϕ, or the current is lagging behind the E. M. F.

From the triangle oda, Fig. 13, we have the relation

$$E^2 = I^2 \left[R^2 + \left(2\pi n L - \frac{1}{2\pi n C}\right)^2\right] \qquad (5)$$

and

$$E = I\sqrt{R^2 + \left(2\pi n L - \frac{1}{2\pi n C}\right)^2} \qquad (6)$$

The expression under the square root sign is, therefore, the impedance of a circuit possessing resistance, self-induction, and capacity, because it is that quantity which multiplied by the current gives the E. M. F.

The impedance of a circuit containing resistance, self-induction, and capacity is equal to the square root of the sum of the squares of the resistance and the difference between the reactance due to self-induction and the reactance due to capacity.

From formula **6**, we have

$$I = \frac{E}{\sqrt{R^2 + \left(2\pi n L - \frac{1}{2\pi n C}\right)^2}} \qquad (7)$$

giving the relation between current and E. M. F. for a circuit containing all three of the above quantities.

10. The tangent of the angle between the E. M. F. and current is given by the expression

$$\tan\phi = \frac{2\pi n L - \frac{1}{2\pi n C}}{R} \qquad (8)$$

So long as the expression $2\pi n L - \frac{1}{2\pi n C}$ is positive, i. e., when the self-induction has a greater effect than the capacity, the component *o e*, Fig. 13, will be above *o a* and the current will lag behind the E. M. F. If the expression is negative, i. e., when the capacity has a greater effect than the self-induction, the component *o e* will be negative, or below the line *o x*, and the current will lead the E. M. F. In such a circuit, therefore, the angle between the E. M. F. and current may vary 90° either way. Fig. 14 shows a case

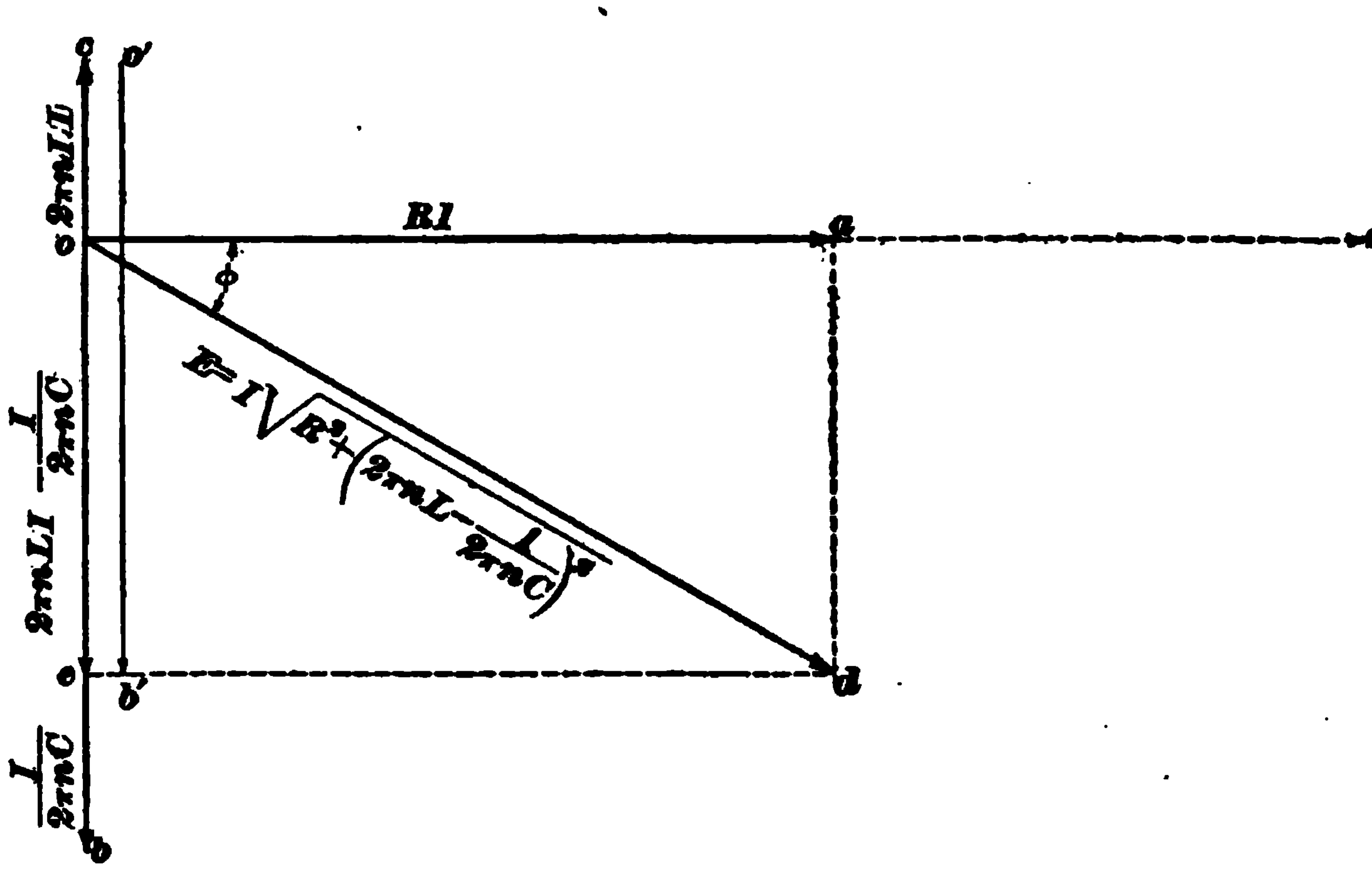


FIG. 14

where the capacity has a greater influence than the self-induction, i. e., *o c* is less than *o b*. Measuring $o' b' = o b$ from *c* gives *o e* as the difference $= 2\pi n L I - \frac{I}{2\pi n C}$, and the E. M. F. $E = o d$. The current in this case is ahead of the E. M. F. by the angle ϕ.

11. When $2\pi n L = \frac{1}{2\pi n C}$, the expression $2\pi n L - \frac{1}{2\pi n C}$ becomes zero, and $\phi = 0$. When this is the case, the current is in phase with the E. M. F. and follows Ohm's law, the capacity and self-induction neutralize each other,

and, though both are present in the circuit, the effect is the same as if neither were there.

In practice, it is almost impossible to obtain complete neutralization of self-induction by capacity; but if the conditions are favorable, it may be approached quite closely.

12. If the self-induction were neutralized by the capacity, the current flowing under a given impressed E. M. F. would be a maximum and would be determined by Ohm's law.

This condition is shown in Fig. 15, where oc and ob are equal and opposite, and $RI = E$ because the current and E. M. F. are in phase.

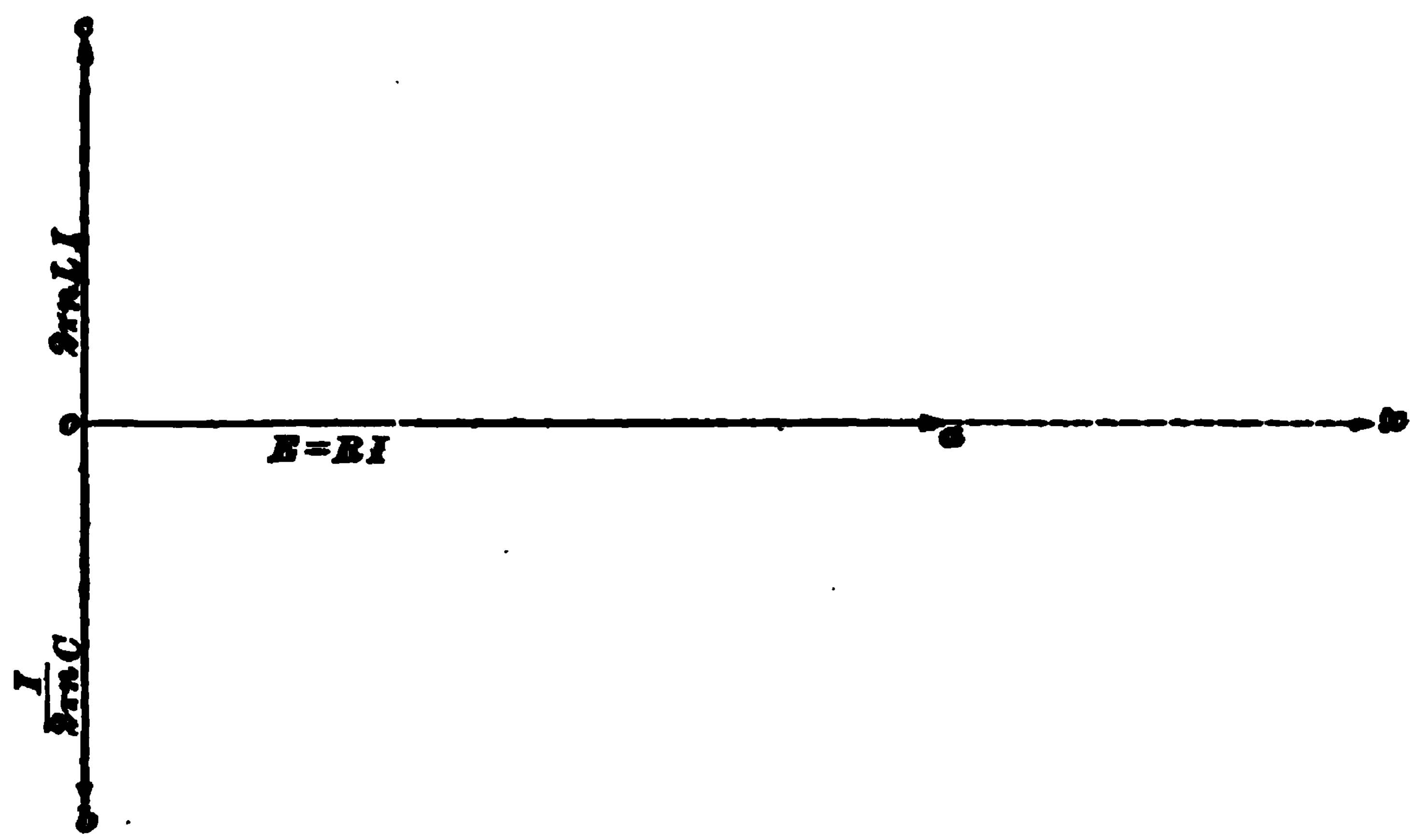


FIG. 15

It should be noted that, with given values of self-induction and capacity, this condition can exist only for one particular value of the frequency, and for any other value the two would not neutralize each other. If

$$2\pi n L = \frac{1}{2\pi n C}$$

we have $n = \sqrt{\frac{1}{4\pi^2 CL}} = \frac{1}{2\pi}\sqrt{\frac{1}{CL}}$ (9)

which gives the value of the frequency corresponding to the

values of C and L. This production of a maximum current in a circuit for a certain critical value of the frequency is known as *electrical resonance.*

13. Resonance sometimes produces peculiar effects in a circuit. If the resistance of the circuit is very low, a neutralization of the self-induction would allow a large current to flow. The E. M. F. across the terminals of the condenser is $\frac{I}{2\pi n C}$, and if I be very large, this pressure may rise to a value very much greater than the impressed E. M. F. In the case of an underground cable, the pressure between the wire and the sheath might rise sufficiently to break down the insulation, while at the same time the E. M. F. supplied by the generator might not be at all high. Usually, however, the frequencies employed in practice are not high enough to make the effects of resonance very common.

14. The following example will show the application of the above formulas to a circuit containing resistance, self-induction, and capacity:

EXAMPLE.—An alternator A, Fig. 16, is connected to a circuit having resistance $R = 100$ ohms, self-induction $L = .25$ henry, and

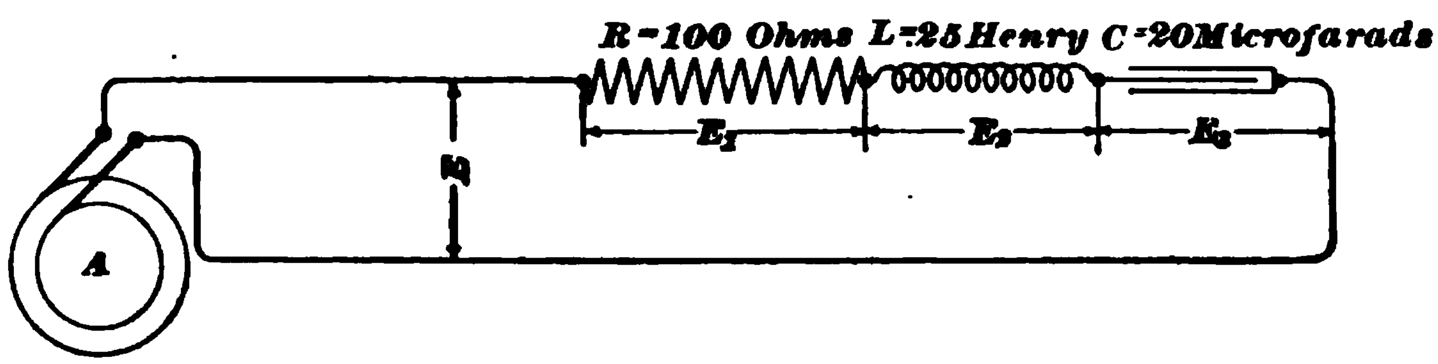


FIG. 16

capacity $C = 20$ microfarads. The current flowing is 5 amperes, and the frequency 60 cycles per second.

1. Find the E. M. F. or drop E_1 across the resistance, drop E_2 across the inductance, drop E_3 across the condenser.

2. Determine whether the current lags behind the impressed E. M. F., or is ahead of it, and by what amount.

3. Find the value of the impressed E. M. F. E necessary to maintain the current of 5 amperes.

SOLUTION.—1. If the inductance $L = .25$ henry, the reactance $2\pi n L = 2 \times 3.14 \times 60 \times .25 = 94.2$ ohms.

The capacity $C = 20$ microfarads, hence the capacity reactance $= \frac{1}{2\pi n C} = \frac{1{,}000{,}000}{2 \times 3.14 \times 60 \times 20} = 132.7$ ohms.

The E. M. F. necessary to overcome resistance $= RI = 5 \times 100 = 500$ volts $= E_1$.

The E. M. F. necessary to overcome inductance $= I \times 2\pi n L = 5 \times 94.2 = 471$ volts $= E_2$.

The E. M. F. necessary to overcome capacity $= \frac{I}{2\pi n C} = 132.7 \times 5 = 663.5$ volts $= E_3$. Ans.

2. Since the E. M. F. necessary to overcome capacity is 663.5 volts and is 90° behind the current, while that to over-

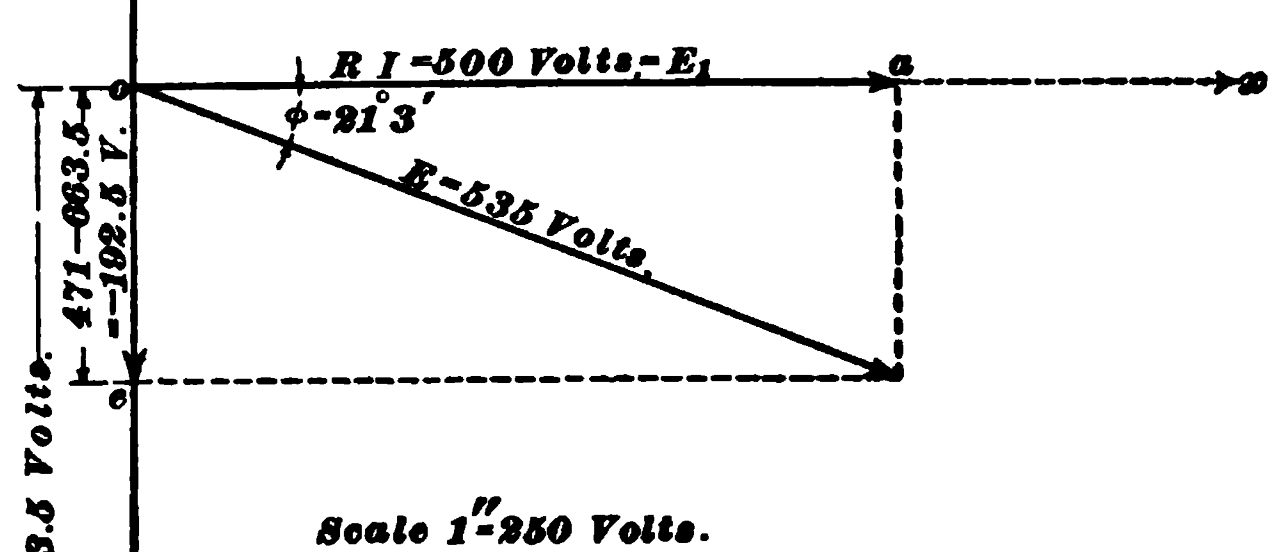


FIG. 17

come self-inductance is only 471 volts and 90° ahead of the current, the resultant component at right angles to the current is $2\pi n L I - \frac{I}{2\pi n C} = 471 - 663.5 = -192.5$, and is 90° behind the current (the negative sign indicating that this component is below the current line). It follows, then, that the impressed E. M. F. E lags behind the current, or the current is in advance of the E. M. F. The relation of the different E. M. F.'s will be readily seen by referring to Fig. 17. The angle by which the current leads is easily found from the figure, because $\tan \phi = \frac{192.5}{500} = .385$, and ϕ is found to be 21° 3', or the current is a little over $\frac{1}{18}$ period ahead of the impressed E. M. F. Ans.

3. The E. M. F. E furnished by the alternator is equal to the current $\times$ impedance; hence,

$$E = I\sqrt{R^2 + \left(2\pi n L - \frac{1}{2\pi n C}\right)^2} = 535 \text{ volts Ans.}$$

In connection with this example, the student should note that while the E. M. F. furnished by the alternator is only 535 volts, the pressure across the terminals of the condenser is 663.5 volts.

15. Resistance, Self-Induction, and Capacity in Parallel.—In this case, shown in Fig. 18, the main current I is the resultant of the three currents I_1, I_2, and I_3. The current I_1 in the non-inductive resistance is in phase with

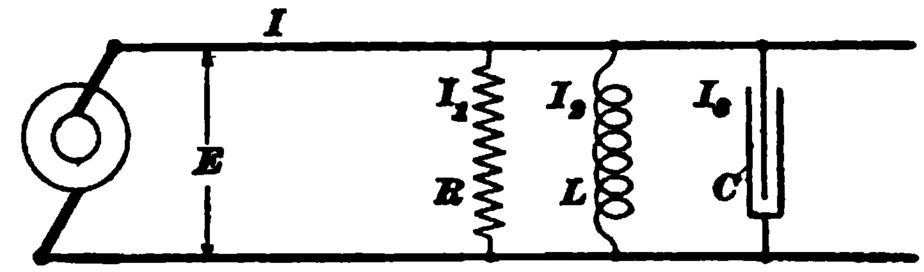


FIG. 18

the E. M. F. and equal to $\frac{E}{R}$. Current I_2 will be equal to $\frac{E}{2\pi n L}$ and is 90° behind E in phase. Current I_3 is equal to $2\pi n C E$ and is 90° ahead of E in phase. The three currents will then be related as shown in Fig. 19. oe is the difference between oc and ob, and is found by subtracting I_2 from I_3, as indicated by the dash line I_2. Of course, if I_2 should happen to be greater than I_3, the resultant current would be in the opposite direction.

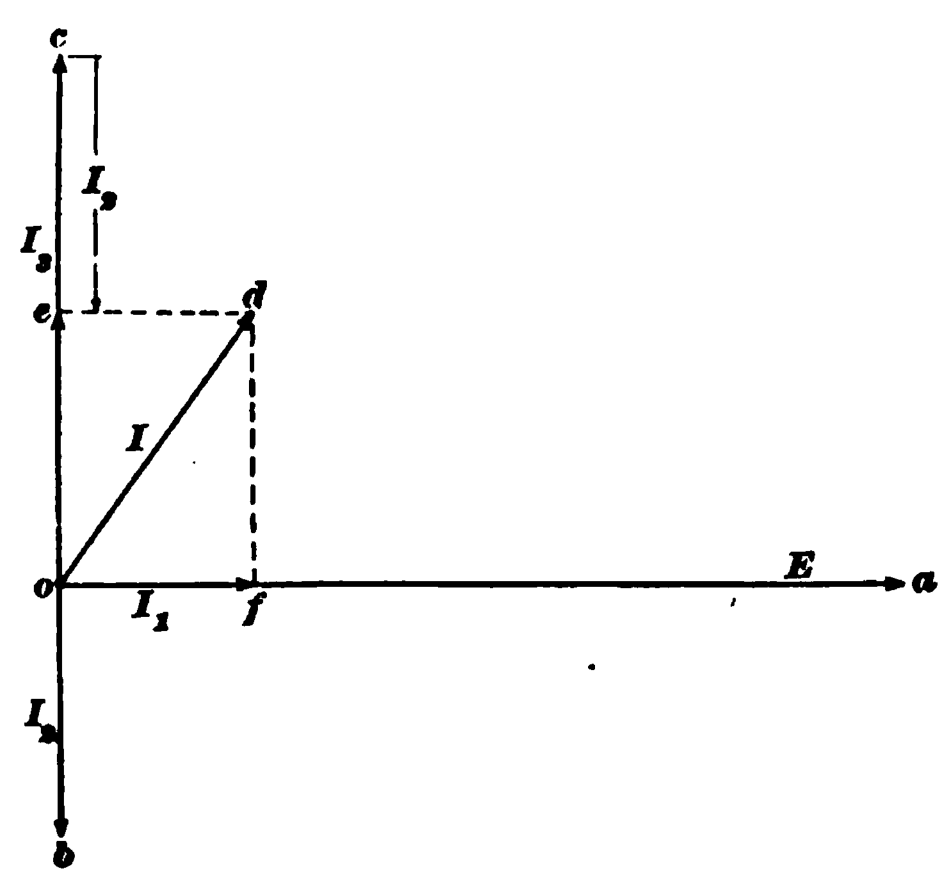


FIG. 19

This resultant oe combined with of, which represents I_1 to scale, gives od, which is the main current I. If the branches containing L and C also contained some resistance, I_2 and I_3 would not be at right angles to oa, but would differ in phase by angles, the tangents of which are readily determined as explained in previous articles.

If such were the case, the diagram would become somewhat as shown in Fig. 20; oc is the resultant of I_2 and I_3, and od is the main current I found by combining oe with of, which represents I_1. It is easily seen from these

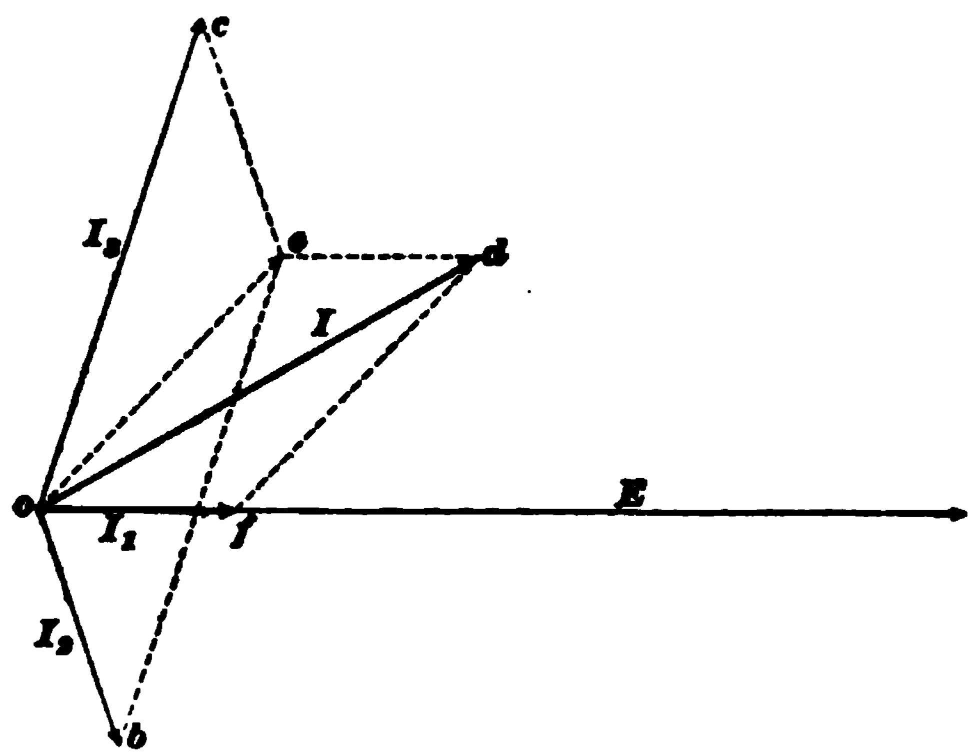


FIG. 20

diagrams that the value of the main current, i. e., the length of od, depends very largely on the phase relation of the currents in the branches.

A striking example of the effect of the phase relation on the main current may be shown by the experiment illustrated in Fig. 21. Lamps l_1, l_2, and l_3 are alike; l_1 is connected in the

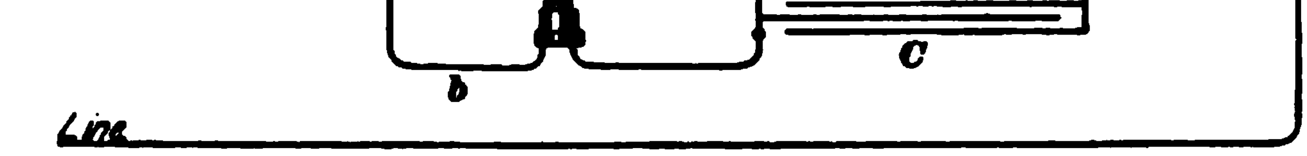


FIG. 21

main circuit, l_2 in the branch containing an adjustable inductance L, and l_3 in the branch containing the condenser C. The inductance L may be adjusted by sliding the coil over

an iron core. If L is adjusted to the proper amount so that the curents in l_2 and l_3 are nearly the same in amount and are out of phase with the E. M. F. by nearly 90°, the main current in l_1 will be very much less than the currents in l_2 and l_3, and lamp l_1 will burn at a dull red, while l_2 and l_3 are burning up to full brilliancy. This state of affairs could not occur with direct current flowing through a divided circuit. The diagram representing the three currents would be as shown in Fig. 22; $o\,c$ represents the current in the condenser, and is nearly 90° ahead of the E. M. F. E; the current in the inductance L is represented by $o\,b$ nearly 90° behind E in phase. The resultant current in lamp l_1 is represented by the line $o\,d$, and this resultant is very much smaller than either of the components $o\,b$ or $o\,c$.

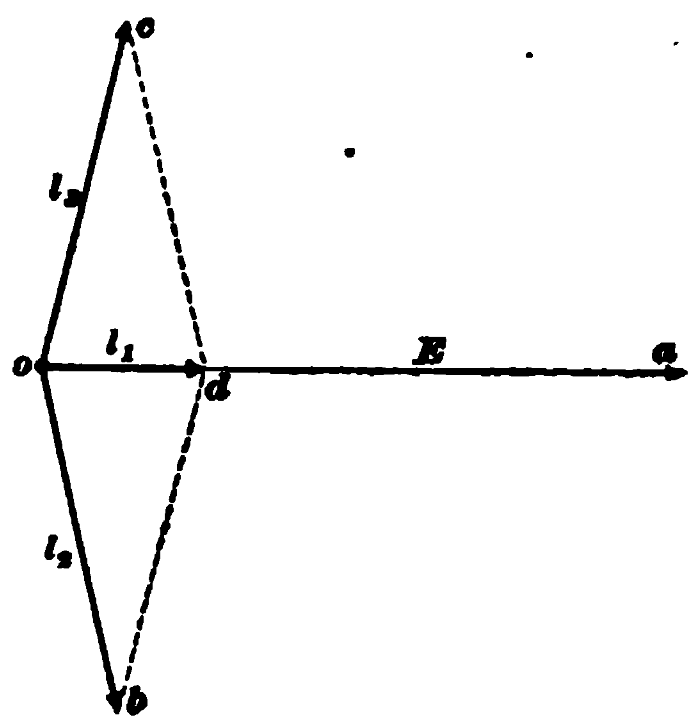


FIG. 22

16. The examples given in the preceding articles will serve to illustrate the composition and resolution of E. M. F.'s in such circuits as are commonly met with. The student should notice that in every case where such E. M. F.'s are combined or resolved, account must be taken not only of their magnitude, but also of their phase relation. For this reason such E. M. F.'s cannot be simply added together, as is done in dealing with direct currents, but the resultant sum must in all cases be obtained by using the polygon or parallelogram of forces. If these phase relations are kept in mind, many of the peculiarities in the behavior of the alternating current are easily understood.

In working out problems, it is always best to draw out a diagram representing the different E. M. F.'s, as it makes the relation between them more easily understood. Quite a number of problems may be solved graphically by adopting convenient scales for the different quantities and laying

out the E. M. F. triangles. The resultant may then be scaled off the drawing and the result obtained more easily than by calculation. Examples of this method have been shown in connection with several of the preceding problems. Unfortunately, however, it is almost impossible to use the graphical method in a large number of cases arising in practice, because the conditions are often such that the quantities entering into the problem result in such long thin triangles and parallelograms that it is almost impossible to scale off any result accurately. In such cases the resultant E. M. F. may be calculated by trigonometry from a knowledge of the sides and angles of the triangle or parallelogram in question.

CALCULATION OF POWER EXPENDED IN ALTERNATING-CURRENT CIRCUITS

17. If a continuous current I flows through a wire of resistance R, the wire becomes heated, and the rate at which work is done in heating the wire is proportional to the square of the current I and to the resistance R; i. e., watts expended $= I^2R$. Since $I = \frac{E}{R}$, we have watts $= EI$. Hence, it may be stated that, in a continuous-current circuit, if we wish to calculate the watts expended, we multiply the current I by the E. M. F. E necessary to force

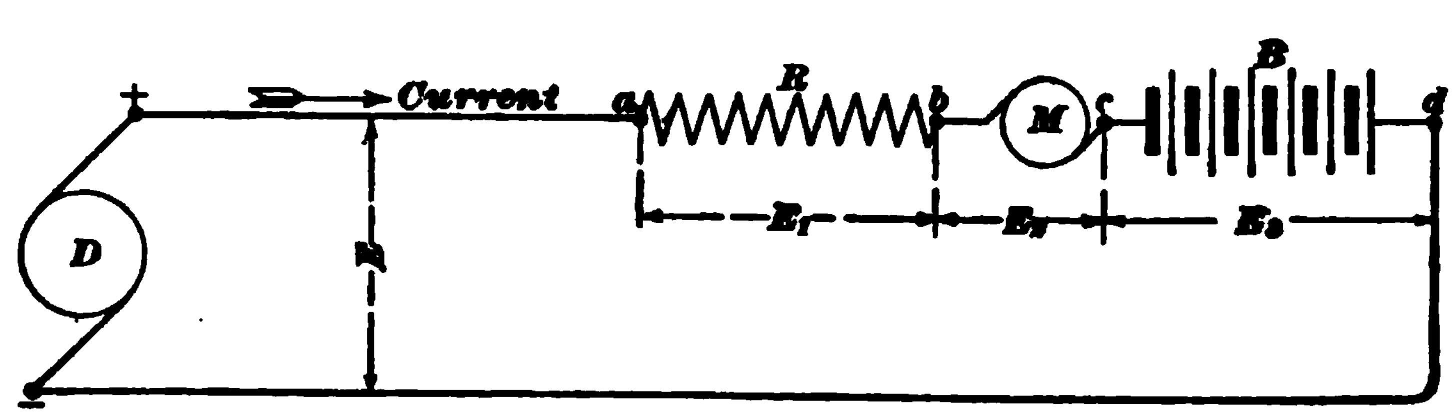


FIG. 23

the current through the circuit. This is also true in a circuit where the energy expended reappears in other forms besides heat. For example, we might have a direct-current dynamo D, Fig. 23, sending current through a circuit $a\,d$,

consisting of a resistance R, a motor M, and a storage battery B. The total power expended in the circuit from a to d will be the product of the current I and the E. M. F. E across the circuit. Part of this energy $= E_1 I$ will reappear as heat in the resistance R, another part, equal to $E_2 I$, will reappear as work done by the motor M, and the energy expended in the battery, $E_3 I$, will be stored up by virtue of the chemical reactions that are caused to take place by the current.

18. If an alternating current be sent through a circuit, the power expended *at each instant* is given by the product of the *instantaneous* values of the current and E. M. F. It is seen at once, then, that the phase relation between the current and E. M. F. will have an important bearing on the power supplied, because the value of the E. M. F. corresponding to any particular value of the current will depend on their phase relation. In alternating-current circuits, therefore, the power expended cannot usually be obtained by simply taking the product of the volts and amperes as is done with direct currents. The effect of difference of phase between current and E. M. F. on the power expended can be well

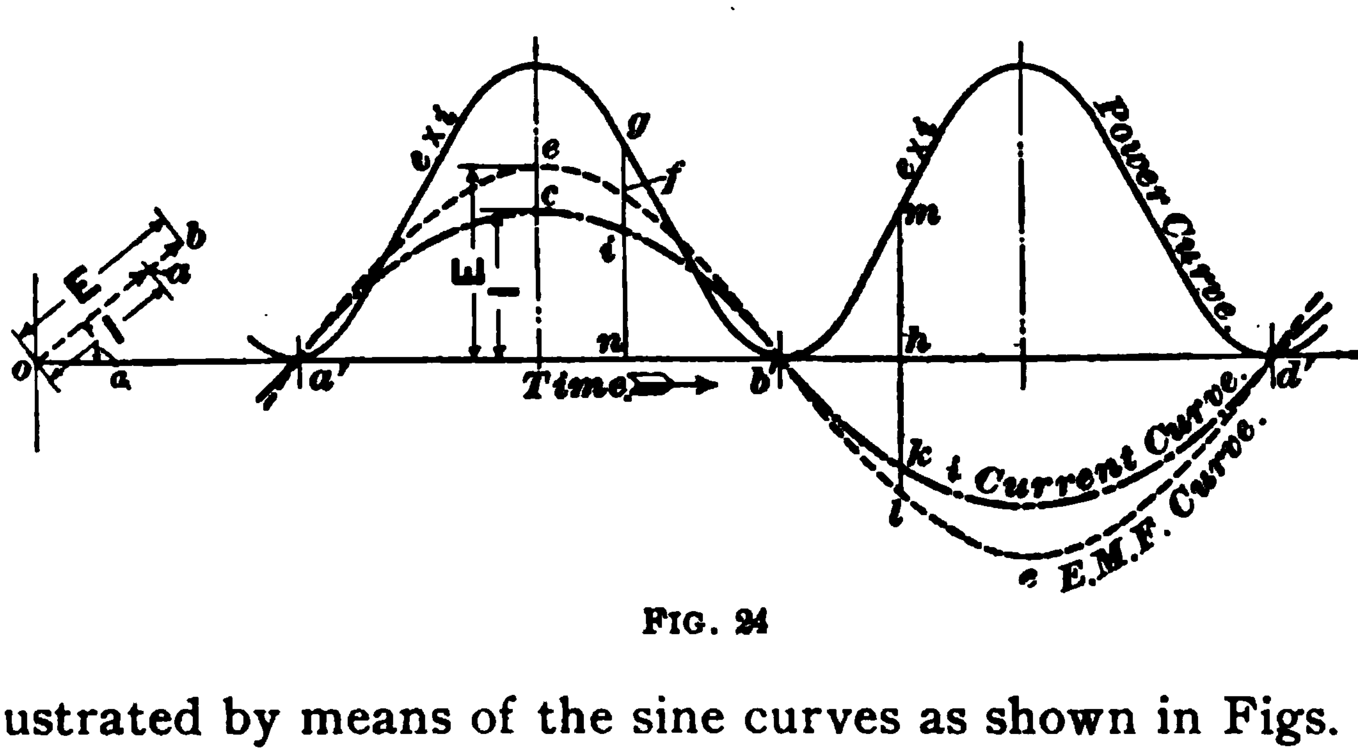


FIG. 24

illustrated by means of the sine curves as shown in Figs. 24 to 28 inclusive. Suppose an E. M. F. of maximum value **E** is in phase with a current of maximum value **I**, as shown in Fig. 24, the current being represented by the dot-and-dash curve, and the E. M. F. by the dotted curve. The power

at any instant, such as that represented by the point *n*, is proportional to the product of the ordinates *n i* and *n f* of the *c* and *e* curves. If, therefore, an ordinate *n g* is erected at *n* proportional to this product, *g* will be a point on the power curve. In this way the power curve shown by the full line is constructed, and it shows the way in which the power supplied to the circuit varies with the E. M. F. and current. It should be noticed that in this case (current and E. M. F. in phase) the power curve lies wholly above the horizontal; that is, the work is all positive, or, in other words, power is being supplied to the circuit. This would be the condition if the current were flowing through a non-inductive resistance.

19. Suppose, however, that the current lags behind the E. M. F. by an angle ϕ less than 90°, as shown in Fig. 25. The power curve is here constructed as before, but it is no longer wholly above the horizontal. The ordinate *f g* of the current curve is positive, while at the same instant that of the E. M. F. curve *f r* is negative; consequently, their product is negative, and the corresponding ordinate of the

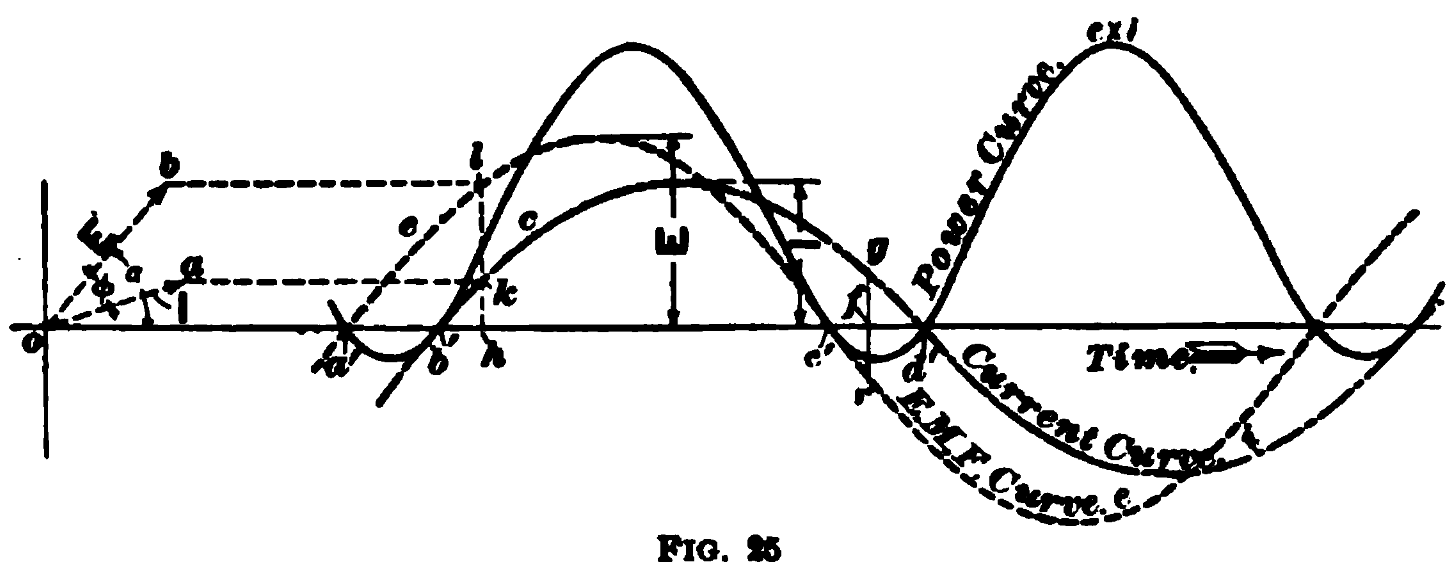


FIG. 25

power curve is below the horizontal. This means that during the intervals of time *a' b'* and *c' d'*, negative work is being performed; or, in other words, the circuit, instead of having work done on it, is returning energy to the system to which it is connected. In Fig. 26 the angle of lag has become 90°, or the current is at right angles to the E. M. F. In this case the power curve lies as much above the axis as

below it, and the circuit returns as much energy as is expended in it. The total work done in such a case is therefore zero, and although a current is flowing, this current does not represent any energy expended. This would be nearly the case if an alternator were supplying current to a circuit having a small resistance and very large inductance, as in this instance the current would lag nearly 90°

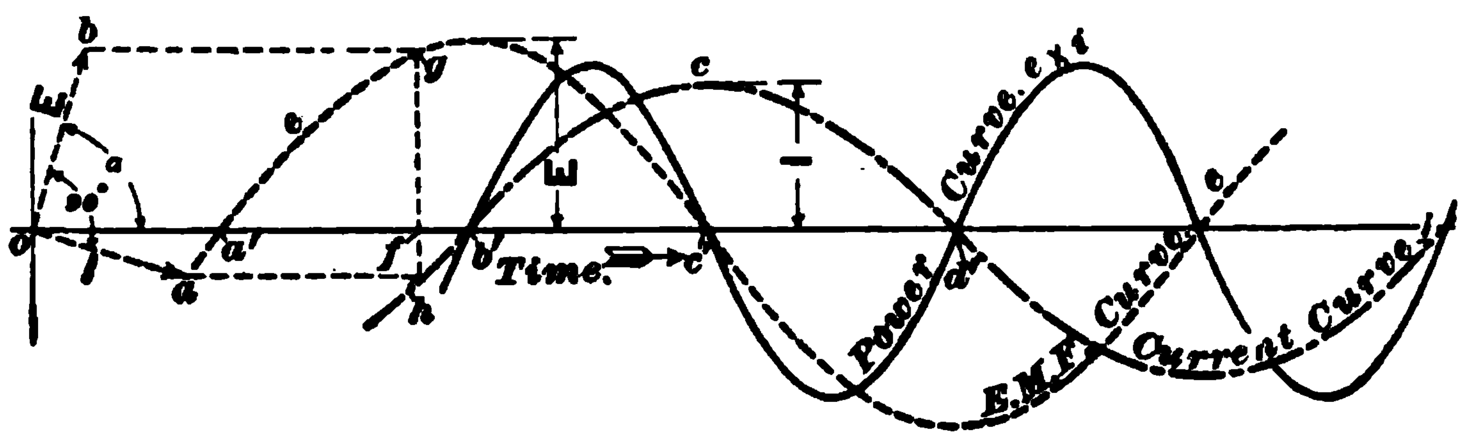


FIG. 26

behind the E. M. F. The primary current of a transformer working with its secondary on open circuit is a practical example of a current that represents very little energy. Such a current at right angles to the E. M. F. is, for the above reasons, known as a *wattless current*, because the product of such a current by the E. M. F. does not represent any watts expended.

20. Another example of a wattless current is that flowing into and out of a condenser when the resistance of the circuit is zero. If the angle of lag becomes greater than 90°,

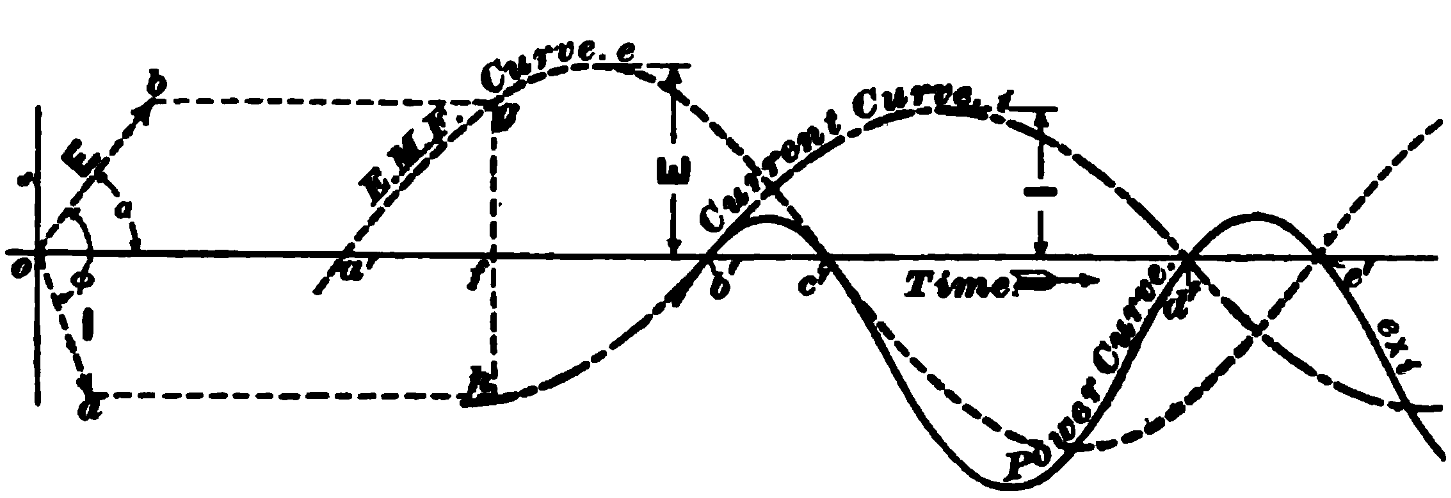


FIG. 27

the greater part of the work becomes negative, as shown in Fig. 27. If the angle of lag becomes 180°, as in Fig. 28,

i. e., if the current and E. M. F. are in opposition, the work done is all negative, and, instead of the alternator doing work on the circuit to which it is connected, the circuit is

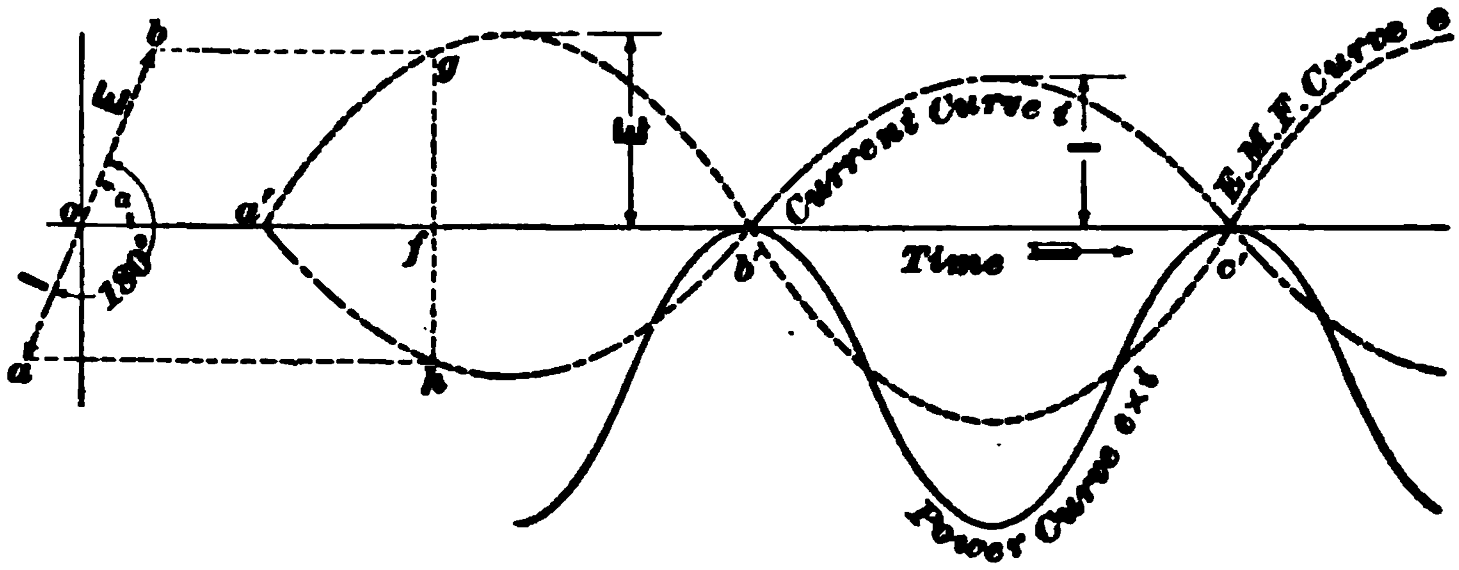


FIG. 28

returning energy to the alternator and running it as a motor. In the above diagrams the relation in phase between the current and E. M. F. is shown in each case by the lines $o\,a$ and $o\,b$, respectively.

21. The power curves in Figs. 25 to 28 show the instantaneous values of the watts expended in a circuit for different values of the angle of lag. What it is usually important to know, however, is the average rate at which energy is expended. Let $o\,a$, Fig. 29, represent the effective value of the current I, which lags behind the effective E. M. F. $E = o\,b$ by an angle ϕ. The average watts expended will be the E. M. F. E multiplied by that component of the current I which is in the same direction as the E. M. F. If a line perpendicular to $o\,b$ be drawn from a to d, the line $o\,d$ represents the component of I, which is in the same direction as $o\,b$, and the watts expended are proportional to the product $o\,b \times o\,d$. The same result would be obtained by multiplying the current $o\,a$ by the component of the E. M. F. in the same direction as the current, i. e., by the product

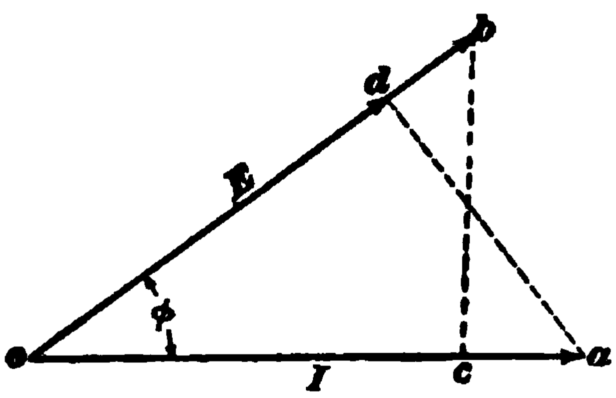


FIG. 29

$oa \times oc$. It is usual to consider the current as resolved into two components, one at right angles to the E. M. F., and the other in the same direction, although it makes no difference in the numerical result which is taken. In Fig. 29 $od = oa \cos\phi$; hence, watts $= od \times ob = oa \cos\phi \; ob = EI \cos\phi$. Or, $oc = ob \cos\phi$, and watts $= oc \; oa = ob \cos\phi \; oa = EI \cos\phi$. It may, therefore, be stated that *the mean power supplied to an alternating-current circuit, in watts, is equal to the effective volts multiplied by the effective amperes times the cosine of the angle by which they differ in phase.*

22. The fact that the product $EI \cos\phi$ gives the watts delivered to a circuit may be proved as follows:

Let ob and oa, Fig. 30, represent the maximum values $\mathbf{E}$ and $\mathbf{I}$ of the E. M. F. and current, differing in phase by the angle ϕ. These lines are supposed to revolve uniformly around o, and the angle α, which is constantly increasing, always represents the angular distance of ob from the reference line ox. The angle ϕ remains constant; that is, ob and oa always keep a fixed distance apart. The instantaneous value of the E. M. F. is given by the expression $e = \mathbf{E} \sin\alpha$. The current $\mathbf{I}$ also passes through a set of instantaneous values and lags behind $\mathbf{E}$ by the constant angle ϕ. The value of the current at any instant is given by the expression $i = \mathbf{I} \sin(\alpha - \phi)$. The product of the instantaneous values e and i gives the instantaneous watts expended, or

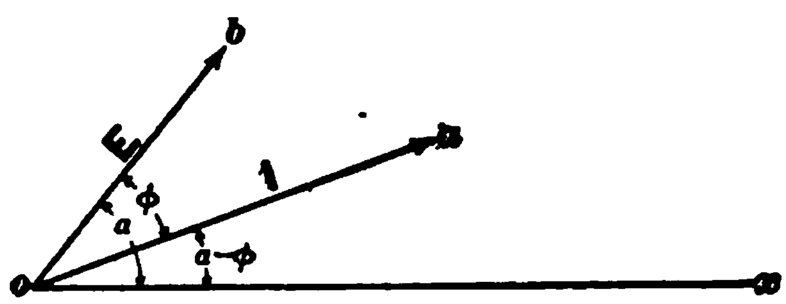


FIG. 30

$$ei = \mathbf{E}\mathbf{I} \sin\alpha \sin(\alpha - \phi)$$

From trigonometry, $\sin(\alpha - \phi) = \sin\alpha \cos\phi - \cos\alpha \sin\phi$;* hence,

$$ei = \mathbf{E}\mathbf{I} \cos\phi \sin^2\alpha - \mathbf{E}\mathbf{I} \cos\alpha \sin\alpha \sin\phi$$

* This proposition may be proved as follows: Let AOB, Fig. 31, be the angle α and POB the angle ϕ; then, $AOP = \alpha - \phi$. From any

and the average value of the watts is

$$\text{av. } e\,i = \text{av. } \mathbf{E}\mathbf{I} \cos\phi \sin^2\alpha - \text{av. } \mathbf{E}\mathbf{I} \cos\alpha \sin\alpha \sin\phi$$

or, since $\cos\phi$ and $\sin\phi$ are constant quantities,

$$\text{av. } e\,i = \mathbf{E}\mathbf{I} \cos\phi \text{ av. } \sin^2\alpha - \mathbf{E}\mathbf{I} \sin\phi \text{ av. } \sin\alpha\cos\alpha$$

The average value of $\sin\alpha\cos\alpha$ is zero, since both pass through positive and negative values alike, and the average value of $\sin^2\alpha = \frac{1}{2}$; hence,

$$\text{average } e\,i = \frac{\mathbf{E}\mathbf{I}}{2}\cos\phi$$

If the maximum values $\mathbf{E}$ and $\mathbf{I}$ are expressed in terms of their effective values, i. e., $\mathbf{E} = E\sqrt{2}$, $\mathbf{I} = I\sqrt{2}$, we have

$$\text{average power} = \text{average } e\,i = E\,I\cos\phi \qquad \textbf{(10)}$$

---

point P, draw $P\,A$ perpendicular to $O\,A$, and $P\,B$ perpendicular to $O\,B$. From B draw $B\,C$ perpendicular to $O\,A$, and from P draw $P\,D$ perpendicular to $B\,C$; $\sin(\alpha - \phi) = \frac{P\,A}{O\,P}$, but $P\,A = D\,C$, and $D\,C = B\,C - B\,D$; hence,

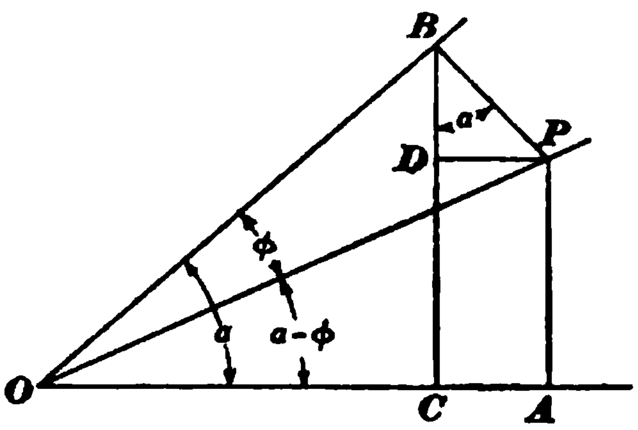


FIG. 31

$$\sin(\alpha - \phi) = \frac{B\,C - B\,D}{O\,P}$$
$$= \frac{B\,C}{O\,P} - \frac{B\,D}{O\,P}$$

Multiplying both numerator and denominator of the fraction $\frac{B\,C}{O\,P}$ by $O\,B$, and the numerator and denominator of $\frac{B\,D}{O\,P}$ by $B\,P$, we may write

$$\sin(\alpha - \phi) = \frac{B\,C}{O\,B} \times \frac{O\,B}{O\,P} - \frac{B\,D}{B\,P} \times \frac{B\,P}{O\,P}$$

Now, $\frac{B\,C}{O\,B} = \sin\alpha$, $\frac{O\,B}{O\,P} = \cos\phi$, because $O\,B\,P$ is a right angle. Also, the angle $D\,B\,P = \alpha$, because $\alpha + O\,B\,C = 1$ right angle, and $O\,B\,C + D\,B\,P = 1$ right angle; hence, $\frac{B\,D}{B\,P} = \cos\alpha$, and $\frac{B\,P}{O\,P} = \sin\phi$, so that we may write

$$\sin(\alpha - \phi) = \sin\alpha\cos\phi - \cos\alpha\sin\phi$$

POWER FACTOR OF A CIRCUIT

23. If an alternating current of I amperes be flowing through a circuit, and the pressure across the terminals of the circuit is E volts, the watts that are apparently expended would be given by the product of the current and E. M. F., that is, by $E \times I$. The real watts expended are however obtained, as proved above, by the product of $E\,I$ and $\cos\phi$. The ratio $\frac{\text{real watts}}{\text{apparent watts}}$ is called the *power factor* of the system.

The **power factor** of a system may then be defined as that quantity by which the apparent watts expended in the system must be multiplied in order to give the true watts. From formula **10**, it will be seen that the power factor is numerically equal to $\cos\phi$, and it is sometimes spoken of as *the cos ϕ of the system.*

24. If the current and E. M. F. are in phase, $\phi = 0$ and $\cos\phi = 1$; consequently, the true watts expended under such circumstances may be obtained by simply taking the product $E \times I$. When the angle of lag is 90°, $\cos\phi = 0$ and the true watts expended is zero, i. e., the current is wattless. When ϕ becomes greater than 90°, $\cos\phi$ becomes negative, thus showing that the circuit is delivering energy to the system to which it is connected. It will be seen, then, that it is quite possible to have large alternating currents flowing under high E. M. F.'s, and at the same time have very little energy expended.

25. The power factor in the case of direct-current systems is always unity; but in cases where alternating current is used, it may vary from unity to zero. In most alternating-current systems the pressure is kept constant, or nearly so; hence, it follows that when a given amount of power is to be transmitted, the current will be smaller if the power factor is high than if it is low. This will, perhaps, be best illustrated by means of an example. Suppose it is desired to

transmit 100 kilowatts over a line by means of alternating current. The load on the line consists principally of motors, and will, therefore, be more or less inductive. We will suppose that the current lags behind the E. M. F. by an angle of 25°. Cos ϕ is then equal to .90, and the power factor will be .90; hence,

$$\text{true watts} = \text{apparent watts} \times .90$$
$$= \text{volts} \times \text{amperes} \times .90$$

We will suppose that the pressure used in transmission is 1,000 volts; then,

$$100{,}000 = 1{,}000 \times \text{amperes} \times .90$$

and the current necessary will be 111.1 amperes. If the power factor had been unity, only 100 amperes would have been required. This example will serve to show the necessity of having the power factor as high as possible.

WATTLESS AND POWER COMPONENTS

26. It was mentioned in connection with Fig. 29 that the current could be looked on as resolved into two components, one at right angles to the E. M. F. and the other in phase with it. This is shown in Fig. 32. The component at right angles to the E. M. F. is known as the **wattless**

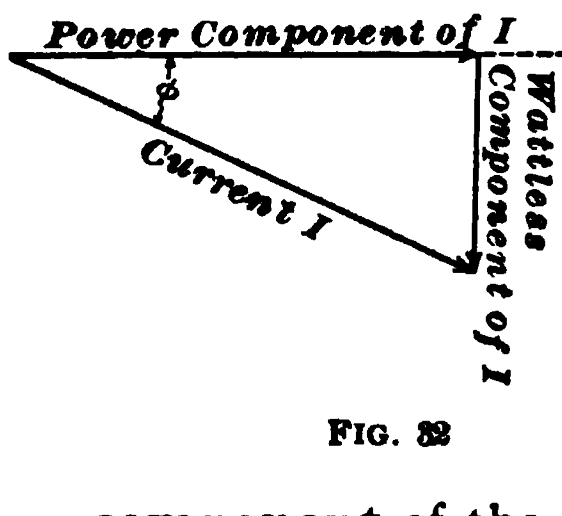


FIG. 32

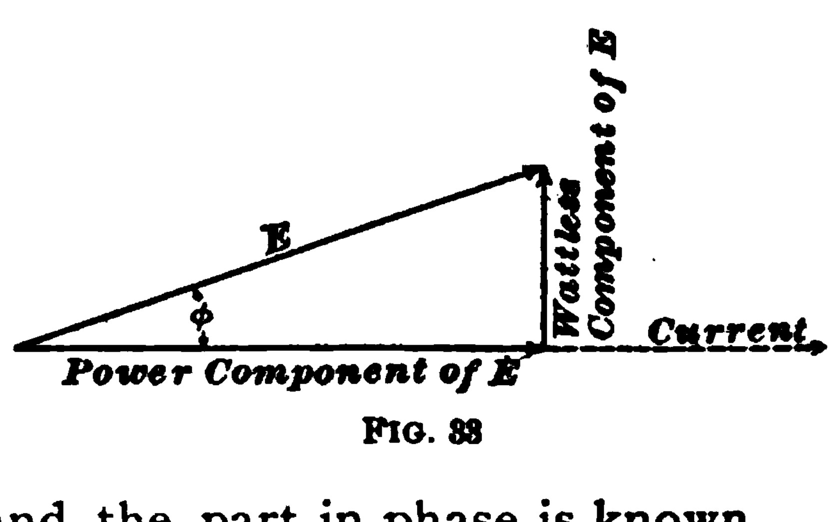


FIG. 33

component of the current, and the part in phase is known as the **power component.** The E. M. F. may, in the same way, be looked on as divided into wattless and power components, as shown in Fig. 33. From these figures it is easily seen that the greater the angle of lag, the larger will be the

wattless component and the smaller the part that is really expending power in the circuit.

27. Although wattless currents do not represent any great amount of power wasted, they are objectionable, because they load up the lines and alternators and thus limit their output as to current-carrying capacity. For example, an alternator might be furnishing a current of, say, 20 amperes to a system having a very low power factor. The actual power delivered would be small, and the engine would not have to work hard to drive the dynamo. At the same time, the current of 20 amperes is circulating through the lines and the armature of the alternator, and thus will load up the lines and heat up the machine. As the current output of the armature is limited to a large extent by this heating, it is seen that the useful current that may be taken from the alternator is cut down by the presence of this wattless component. Alternating-current apparatus, such as induction motors, etc., are always designed so as to have as high a power factor as possible consistent with economy. The use of condensers has been suggested for neutralizing the self-induction, thus increasing the power factor, and one manufacturing company has used condensers in connection with induction motors to cut down the lag in the current.

EXAMPLE.—An alternator generating an E. M. F. of 1,000 volts at a frequency of 60 cycles per second supplies current to a system of which the resistance is 100 ohms and the inductance .3 henry. Find the value of the current, angle of lag, power factor, apparent watts, and true watts.

SOLUTION.—We have

$$I = \frac{E}{\sqrt{R^2 + (2\pi n L)^2}} = \frac{1{,}000}{\sqrt{100^2 + (2 \times 3.14 \times 60 \times .3)^2}}$$

$$= \frac{1{,}000}{150.8} = 6.63 \text{ amperes}$$

Reactance $= 2\pi n L = 113.04$ ohms.

$$\tan \varphi = \frac{2\pi n L}{R} = \frac{113.04}{100} = 1.13$$

hence, ϕ = angle of lag = 48° 30′; power factor = $\cos \phi$ = .662; apparent watts = EI = 1,000 × 6.63 = 6,630; real watts = $EI \cos \phi$ = 1,000 × 6.63 × .662 = 4,389. Ans.

The effect of the self-induction in the above example is, therefore, to cause a lag of 48° 30′, and by so doing the current of 6.63 amperes is equivalent to only 4,389 watts transmitted; whereas, if there were no inductance and $\cos \phi = 1$, this current would have been equivalent to 6,630 watts.

TRANSMISSION LINES

28. In transmitting power over lines by means of the electric current, a certain loss of energy always occurs, due to the resistance of the wire. This loss cannot be avoided, and all that can be done is to keep it down to within reasonable limits. Of course, the loss can be made as small as we please by increasing the size of the line conductor, but it is less expensive to allow a certain loss than to make the conductor very large. The lost energy in transmission lines varies greatly and depends largely on local conditions. Quite often it is about 5 or 10 per cent. of the power transmitted, and in some cases it is more than this, especially on long lines. The loss in the line results in a falling off in pressure between the station and the distant end, the number of volts decrease, or *drop*, as it is called, being obtained, in the case of continuous-current circuits, by multiplying the current by the resistance of the line. Evidently the drop will increase as the load or current increases, and if the pressure at the receiving end is to be kept constant at all loads, the pressure at the station must be increased as the current increases.

29. The calculation of the size of wire to transmit a given amount of power over a given distance with a specified loss is a simple matter in the case of a direct-current circuit, as it simply requires a wire of such a size that the resistance of the circuit shall not cause the loss to exceed

the specified amount. For example, suppose it is required to transmit 20 kilowatts a distance of 2 miles by means of direct current. The voltage at the delivery end is to be 500, and the loss is not to exceed 10 per cent. of this, i. e., the allowable drop is 50 volts at full load. The full load current equals

$$\frac{\text{watts}}{\text{volts}} = \frac{20000}{500} = 40 \text{ amperes}$$

$$R \times I = 50 \text{ volts}$$

$$R = \frac{50}{40} = 1.25 \text{ ohms}$$

The resistance of the whole length of wire from the station and back, or 4 miles, must not exceed 1.25 ohms, or the resistance per mile = .3125 ohm. By consulting a wire table, this is found to be about a No. 000 B. & S. wire.

30. Self-Induction of Line.—As long as alternating-current lines are not very long and the power is delivered to a load that is largely non-inductive, as, for example, a load of lamps, it is sufficiently accurate to estimate the size of the wire, or the volts drop corresponding to a given size, by applying the same rules as used for direct current.

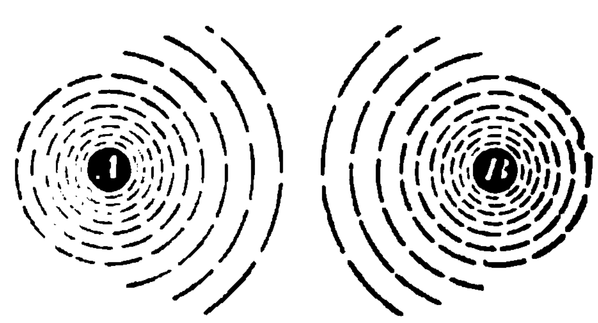


FIG. 34

However, if the lines are long and if the load is more or less inductive, as a load of induction motors, it is not safe to apply the direct-current methods. The reason for this is twofold. In the first place, a long line has considerable self-induction, and in the second, the effect of the self-induction of the line and the load is to throw the E. M. F. applied to the line out of phase with the current. Suppose A and B, Fig. 34, represent a cross-section of two line wires in which an alternating current is flowing. The current will set up magnetism between the wires, as indicated by the dotted circles, and as this magnetism is constantly changing with the changes in the current, an induced

E. M. F. is set up that causes the drop in the line to be greater for a given current than it would if direct current were flowing. The farther the wires are apart, the greater will be the self-induction, because there will then be a larger area for the lines to thread between the wires. In cables, where the wires are insulated and twisted together, there is very little self-induction, but on overhead lines, where the wires must be spread several inches apart, it may have quite a decided effect on the drop. The self-induction of parallel copper wires may be calculated approximately from the following formula:

$$L = .0805 + .74 \log \frac{d}{r} \qquad \textbf{(11)}$$

where L = inductance, per mile of wire, in millihenrys (thousandths of a henry);
d = spread of wires (center to center);
r = radius of wire.

d and r may be expressed in any convenient unit so long as the same unit is used for each.

EXAMPLE.—(*a*) Find the inductance in millihenrys of 1 mile of line consisting of two No. 0000 B. & S. wires strung 24 inches apart. (*b*) Find the reactance of this mile of line, assuming the frequency to be 60. (*c*) Calculate the impedance of the line.

SOLUTION.—(*a*) In this case the diameter of the wire is .46 inch, or the radius is .23 inch. The value of d is 24 inches; hence, the inductance of each of the wires will be $L = .0805 + .74 \log \frac{24}{.23} = 1.575$, and the inductance of the two lines will be $1.575 \times 2 = 3.150$ millihenrys. Ans.

(*b*) The reactance will be $2 \pi n L$, where L is the inductance in henrys. 3.15 millihenrys = .00315 henry; hence, reactance = $2 \times 3.14 \times 60 \times .00315 = 1.187$ ohms. Ans.

(*c*) The impedance will be equal to $\sqrt{R^2 + (2 \pi n L)^2}$. The resistance per mile of No. 0000 is .259 ohm, and the resistance of 2 miles would be .518 ohm. The impedance of the 2 miles of line would, therefore, be $\sqrt{(.518)^2 + (1.187)^2} = 1.295$. Ans.

Table I shows the values of reactance and impedance of bare copper wires as given by Emmet. These values differ

TABLE I

Gauge No. B. & S.	Resistance in Ohms Per Mile of Wire	Reactance and Impedance in Ohms Per Mile of Wire at a Frequency of 60						Reactance and Impedance in Ohms Per Mile of Wire at a Frequency of 125					
		12 Inches Between Centers		18 Inches Between Centers		24 Inches Between Centers		12 Inches Between Centers		18 Inches Between Centers		24 Inches Between Centers	
		Reactance	Impedance	Reactance	Impedance	Reactance	Impedance	Reactance	Impedance	Reactance	Impedance	Reactance	Impedance
0000	.259	.508	.570	.557	.615	.591	.646	1.06	1.092	1.17	1.190	1.23	1.260
000	.324	.523	.616	.573	.658	.607	.686	1.09	1.138	1.20	1.237	1.26	1.305
00	.412	.534	.682	.588	.725	.618	.749	1.12	1.194	1.23	1.297	1.29	1.357
0	.519	.550	.756	.603	.796	.633	.818	1.15	1.258	1.26	1.360	1.32	1.415
1	.655	.565	.865	.614	.896	.648	.920	1.18	1.349	1.28	1.436	1.35	1.500
2	.826	.580	1.008	.629	1.038	.663	1.060	1.21	1.466	1.31	1.550	1.38	1.610
3	1.041	.591	1.196	.644	1.223	.674	1.240	1.24	1.610	1.34	1.700	1.41	1.750
4	1.313	.606	1.448	.656	1.467	.690	1.480	1.26	1.820	1.37	1.890	1.44	1.940
5	1.656	.620	1.760	.670	1.780	.704	1.800	1.30	2.100	1.40	2.170	1.47	2.220
6	2.088	.633	2.180	.685	2.200	.720	2.210	1.32	2.460	1.43	2.510	1.49	2.560
7	2.633	.647	2.710	.700	2.720	.730	2.730	1.35	2.930	1.46	3.000	1.52	3.040
8	3.320	.662	3.380	.712	3.390	.742	3.400	1.38	3.590	1.48	3.630	1.55	3.660
9	4.186	.677	4.210	.727	4.220	.761	4.230	1.41	4.390	1.51	4.430	1.58	4.450
10	5.280	.688	5.320	.742	5.330	.776	5.340	1.44	5.470	1.54	5.500	1.62	5.530

slightly from those given by formula **11,** owing to the number of decimal places used in making the calculations. The difference is, however, not sufficient to be of practical importance.

31. Line Capacity.—The electrostatic capacity of overhead lines is usually of such small amount that it does not materially affect the drop unless the line is a very long one. In all except long transmission lines or long lines of underground cable, the line capacity may be neglected. The capacity per mile of two parallel wires stretched in air may be calculated by the following formula:

$$C = \frac{.0194}{\log \frac{d}{r}} \qquad \textbf{(12)}$$

where C = capacity in microfarads per mile of line;
d = spread of wires;
r = radius of wire.

d and r must be expressed in terms of the same unit.

EXAMPLE.—Find the capacity of 3 miles of line made up of two cables $\frac{1}{4}$ inch in diameter, strung 12 inches apart.

SOLUTION.—In this case $d = 12$ inches; the diameter of the wire is $\frac{1}{4}$ inch, or $r = \frac{1}{8}$ inch; $\frac{d}{r} = 48$, and $\log 48 = 1.68124$; hence, $C = \frac{.0194}{1.68124}$ $= .0115$ microfarad per mile, and the total capacity is $.0115 \times 3$ $= .0345$ microfarad. Ans.

32. Drop in Alternating-Current Lines. — The amount of **drop,** i. e., the difference in voltage between the station end and the receiving end of the line, in an alternating-current circuit depends both on the impedance of the line and also on the kind of load that the current is supplied to. The relations are shown in Fig. 35. Let $f = \cos \phi$ be the power factor of the load. Then the E. M. F. E' at the end of the line where the load is situated may be considered as made up of two parts, one of which $o\,a$ is in phase with the current, and the other $a\,b$ at right angles to the current. $o\,b$ represents the E. M. F. E' at the receiving end

of the line. The E. M. F. supplied by the generator must be the resultant of E' and the E. M. F. necessary to overcome the impedance of the line. The E. M. F. necessary to overcome the line resistance will be in phase with the current and will be represented by $o\,c$. The E. M. F. necessary to overcome the line reactance will be represented by $c\,d$ at right angles to the current line. Then, $o\,d$ is the E. M. F.

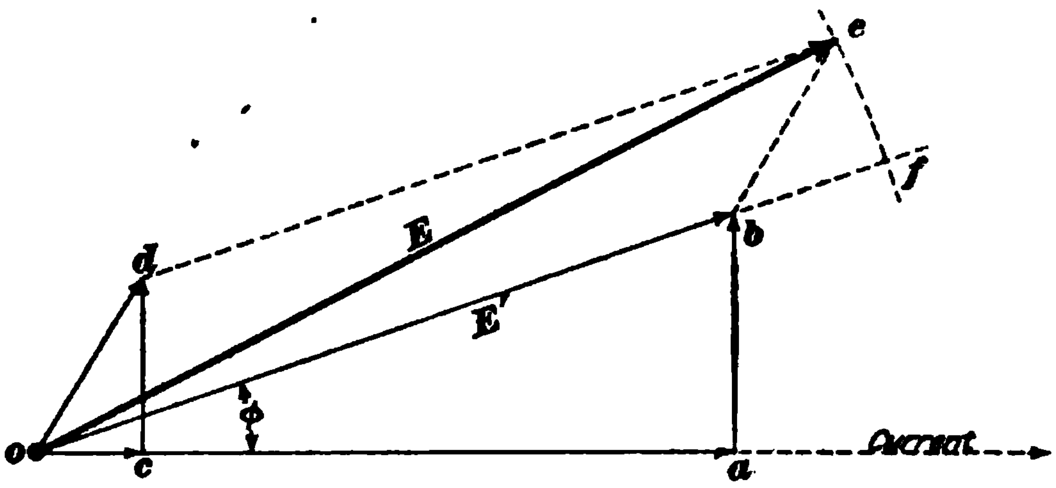


FIG. 35

necessary to overcome the line impedance, and $o\,e$ is the resultant of E' and $o\,d$, and, therefore, represents the generator E. M. F. E. The difference between E and E' is the drop in the line, and is represented to scale by $b\,f$, which is obtained by striking an arc with o as center and $o\,e$ as radius. For a given line, the resistance and reactance are easily calculated as explained above; hence, the triangle $o\,c\,d$ can be constructed.

33. The required terminal E. M. F. E' is usually known, and the angle ϕ is known from the nature of the load to be supplied. For example, if the load were all lights, the power factor would be very nearly 1 and the angle ϕ could be made zero. If the load were all induction motors, the power factor, $\cos \phi$, might be about .85, corresponding to an angle of lag of a little over 31°. By laying out the diagram, to scale, the drop can be readily obtained. In case the problem is to obtain the size of wire required to limit the drop to a certain amount, the above diagram can be applied by using the cut-and-try method. A rough estimate of the size can first be made by treating it as a direct-current problem, and the size so determined applied to the

above diagram will give a general idea as to how much the allowable drop would be exceeded with alternating current. Two or three trials will usually be sufficient to show what size of wire will be necessary. From Fig. 35 it is easily seen that the drop in an alternating-current line cannot be obtained by multiplying the current by the impedance of the line, although if the load were very nearly non-inductive the product of current by impedance would give the line drop quite closely. In making calculations and in laying out diagrams as shown in Fig. 35, the triangles often become so long and thin that it is difficult to scale off results accurately, and it is convenient to use approximate formulas for estimating the line drop and determining the size of wire for a given transmission system. Formulas for making these calculations will be given later.

ALTERNATING-CURRENT MEASURING INSTRUMENTS

34. In measuring alternating E. M. F.'s and currents, we usually wish to know the square-root-of-mean-square, or effective, values, as these are used in most of the ordinary calculations. The maximum or instantaneous values are not used to any great extent. Ammeters and voltmeters for use on alternating-current circuits, as a general rule, therefore, indicate effective values, and most of such instruments will, if standardized by means of direct current, read effective values when connected to alternating-current circuits.

There is not such a large variety of alternating-current instruments as of direct-current, since a large number of instruments adapted for direct-current work will not act at all with alternating current. Generally speaking, an instrument that will give indications with alternating current will work also with direct current, but the reverse is by no means true. Take, for example, the Weston direct-current

ammeters and voltmeters, which are widely used for direct-current measurements. The current flowing in a swinging coil reacts on a permanent field and thus produces a deflection. If such an instrument were connected to an alternating-current circuit, the coil would not move, because the current would be continually changing direction, and there would be as much tendency to turn one way as the other. These instruments are, therefore, not suitable for alternating-current circuits, and should never be connected to them. This is true of any class of instruments where a deflection is produced by the current reacting on a constant magnetic field.

CLASSES OF INSTRUMENTS

35. For use in connection with alternating currents we are practically limited to four classes of instruments.

1. Hot-wire ammeters and voltmeters.
2. Plunger, or electromagnetic, ammeters and voltmeters.
3. Electrodynamometers (ammeters, voltmeters, wattmeters).
4. Electrostatic voltmeters.

HOT-WIRE AMMETERS AND VOLTMETERS

36. The first class of instruments depends for its action on the heating effect of the current. One type of **hot-wire voltmeter** is the Cardew. This instrument will indicate equally well on either direct or alternating current, and when it is calibrated with direct current, it will give the effective E. M. F. if connected to alternating-current mains.

The hot-wire voltmeter may be used to measure current by connecting it across the terminals of a known non-inductive resistance, as shown at R, Fig. 36. The voltmeter V in this case measures the drop from e to f through the resistance, this drop being equal to $R I$; hence, if R is known, I can be at once obtained, or the scale of the instrument

might be so marked as to give the current directly. Hot-wire instruments may be shunted in this way because they possess very little self-induction. Alternating-current instruments that operate on the electromagnetic principle,

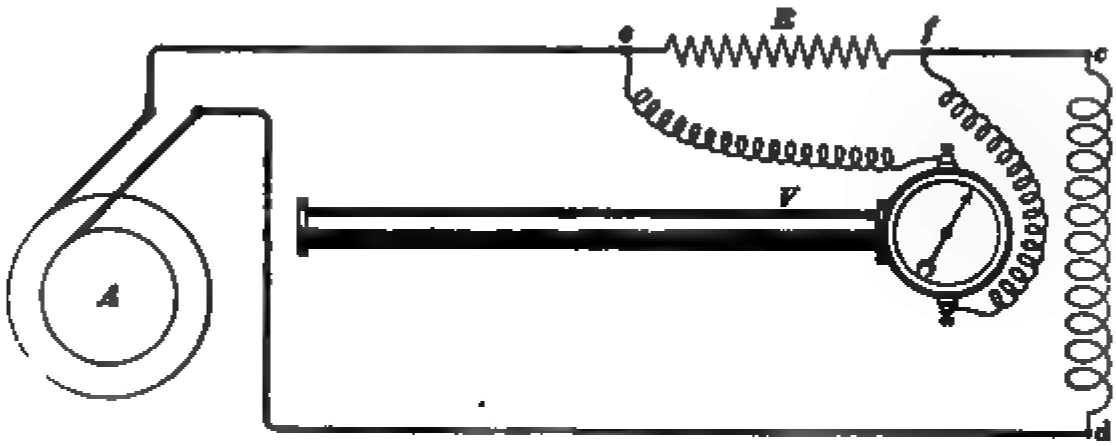


FIG. 36

and, therefore, have more or less self-induction, cannot be used in connection with shunts and give accurate results.

37. Stanley Hot-Wire Instruments.—The most prominent example of the hot-wire type as used at present in America is the **Stanley instrument,** manufactured under the patents of Hartmann & Braun. These instruments are made for measuring either current or voltage, and when used to measure current, a shunt is employed, as shown in Fig. 36. The ammeter and voltmeter have the same general appearance, shown in Fig. 37. The parts are mounted on a hard-rubber base held in a brass frame, so that the working parts are

FIG. 37

thoroughly insulated from the case of the instrument. The wire that is heated by the current is up under the scale, and, hence, is not shown in Fig. 37. The knob *n* is for adjusting the pointer to the zero point in case the pointer should not return exactly to zero. The movements of the needle are damped by a small aluminum disk *s* that swings between the poles of the permanent magnet *m*, thus making

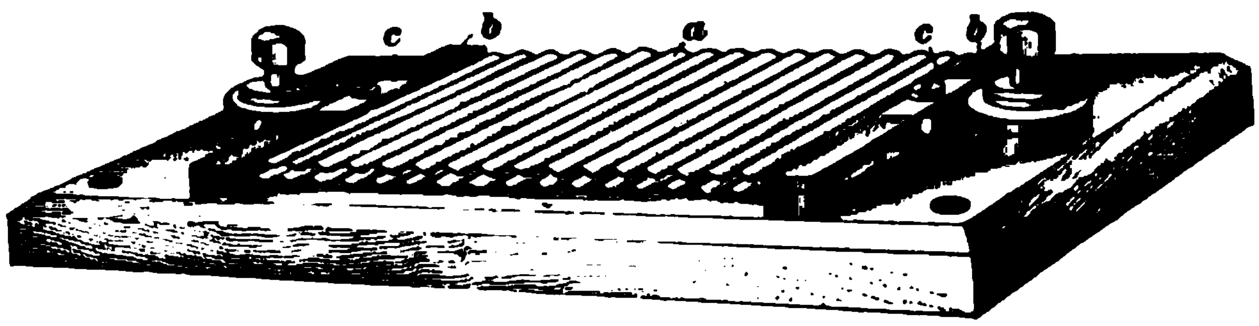


FIG. 38

the instrument very dead beat. Fig. 38 shows the style of shunt used in connection with the ammeter; it consists of low resistance strips *a* connected to heavy terminals *b*. The ammeter is connected to the shunt by means of flexible cables furnished with the instrument. The cables are attached at *c c*, and it is important to see that the number on the cables corresponds to the number on the instrument, otherwise the indications will not be correct. In the ammeter the hot wire is tapped at one or more points by means of flexible silver strips, and the sections of the wire are connected in parallel. This allows a long wire to be used, and yet makes the resistance so low that a small drop across the shunt is sufficient to operate the instrument. One of these silver strips is seen in Fig. 37, projecting below the central part of the scale. As already mentioned, an alternating-current ammeter cannot be shunted unless it has negligible self-induction. This type of instrument has practically no self-induction, but an appreciable amount might be introduced by coiling up the cables leading to the instrument. If these cables are too long, they should on no account be shortened up in this manner; the slack should be taken up by doubling the cables back and forth on themselves, not by winding up into a coil.

Fig. 39 shows the principle of operation of the Stanley hot-wire instruments. *a b* is the wire that is heated by the passage of the current. This wire is stretched tightly between two supports mounted on a base that expands and contracts, with changes in the room temperature, at the same rate as the wire. This compensates for changes in the temperature of the room in which the instrument is placed. Near the middle point is attached a second fine wire *c*, which is connected to the fixed post *g*. To this second wire is

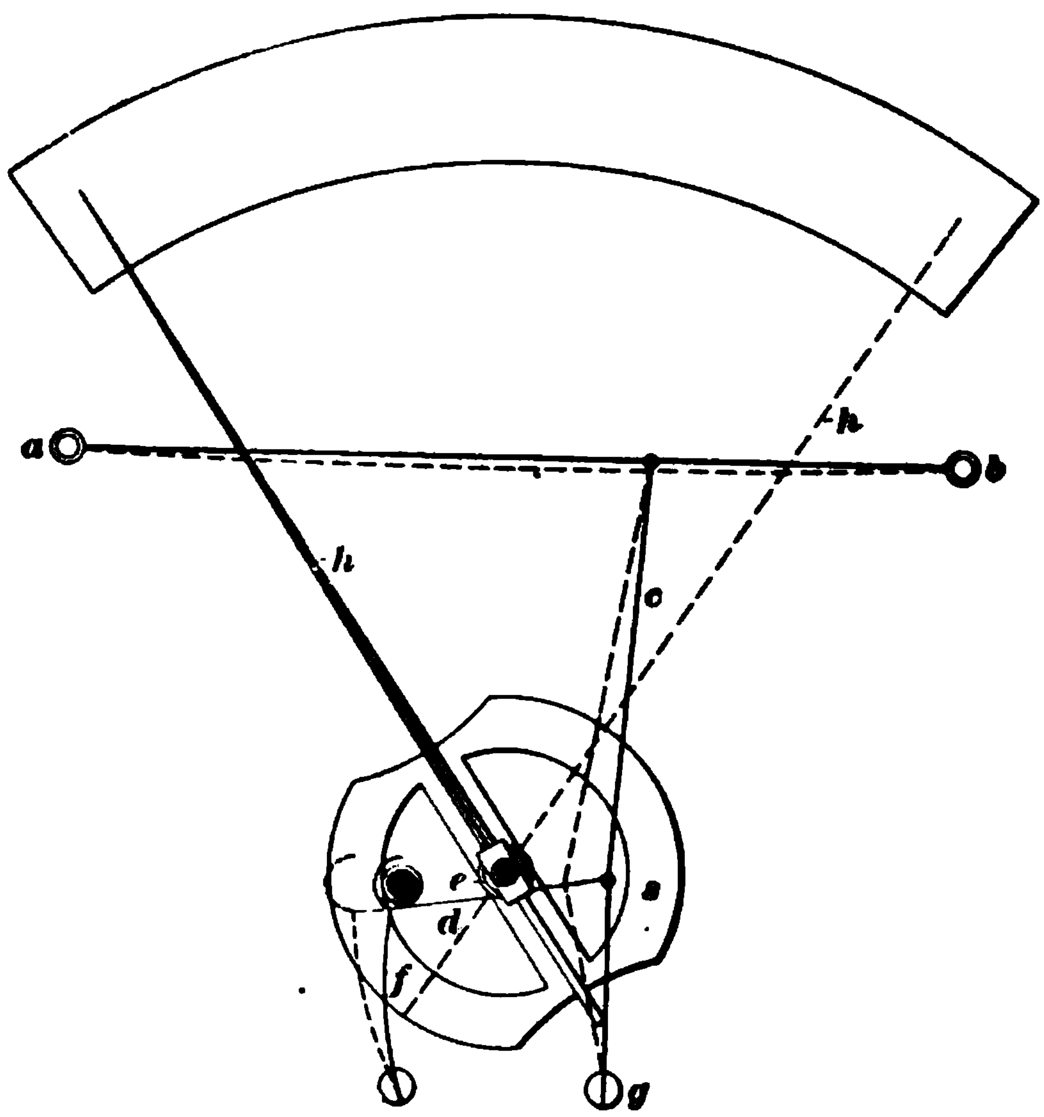


FIG. 39

attached a third wire *d*, which passes around the small pulley *e* and is held taut by the flat spring *f*. This wire is very fine and offers very little resistance to the bending action around the small pulley. The pointer *h* is attached to the vertical shaft that carries the pulley, and this shaft also carries the aluminum damping disk *s*; the shaft is mounted on jewel bearings, so as to turn with the minimum amount of friction. It will be noted that, by making use of the construction shown in the figure, a very small expansion of the

heated wire is sufficient to cause a movement of the needle over the scale. Since the wire is stretched tightly between the supports *a b*, a very small expansion is sufficient to cause a considerable sag, and this in turn permits of a large deflection of the pointer. The whole system being held taut by the spring, any slight expansion of *a b* is transmitted to the pointer and the movement is largely multiplied. The dotted outlines show, in an exaggerated way, the position taken up by the wires when a current is passed through *a b*. This method of causing the expansion of the wire to operate the needle is extremely simple, and at the same time gives great sensitiveness. Hot-wire instruments have the advantage that they can be used on circuits of any frequency and are equally well adapted to either direct or alternating current.

PLUNGER AND MAGNETIC-VANE INSTRUMENTS

38. Instruments of the **plunger** type have been used quite largely for ammeters and voltmeters in central stations, but they are being superseded by other types. In the old-style Westinghouse plunger ammeter, the conductor that carries the current forms a vertical coil within which hangs a straight core made of iron wire. This core is suspended from one arm of a balance, on the other arm of which is a weight that counterbalances the weight of the iron core, so that the pointer, which is rigidly fastened to the balance arm, will normally point to zero on the scale. As the strength of the current flowing through the coil varies, the pull on the plunger varies; consequently the needle is deflected.

The Westinghouse plunger voltmeter, which is similar in principle to the ammeter, has a coil with a large number of turns, in series with which is connected a high resistance in order to limit the current through the voltmeter. The so-called **magnetic-vane instruments** are a modification of the plunger type. A small flat vane of iron, to which a pointer is attached, is mounted on an axis inside a coil. The tendency of the coil to rotate the vane is opposed by a spiral spring.

39. Inclined-Coil Instruments.—Fig. 40 illustrates the principle of an alternating-current instrument that has

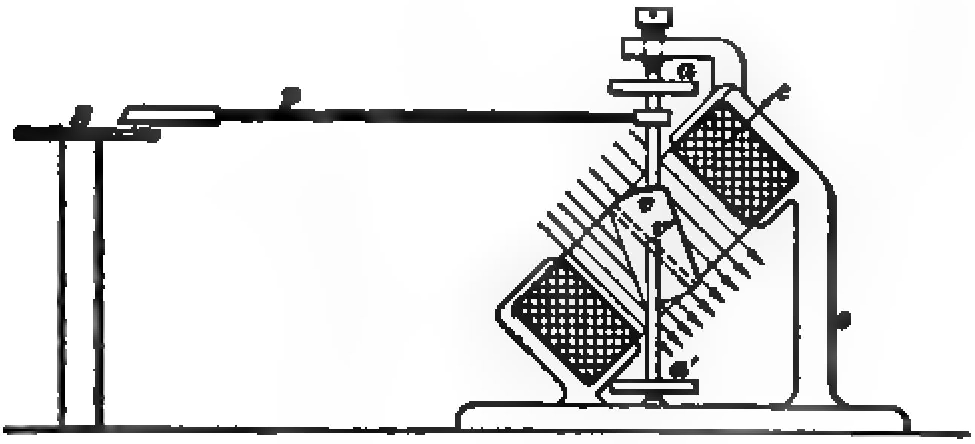


Fig. 40

been largely used for switchboard work in alternating-current plants. It is a modification of the magnetic vane type, and is known as the **Thomson inclined-coil instrument.** It is made and used by the General Electric Company. A circular coil *c*, shown in section, is mounted with its axis inclined to the horizontal. Through the center of the coil passes a vertical shaft that carries the pointer *p*. A small vane of iron *v* is mounted on the shaft at an angle, and the movement of the swinging system is controlled by the two flat spiral springs *a*, *a'*. When a current flows through the coil, lines of force will thread it as shown by the arrows. The iron vane *v* will tend to turn so that it will lie parallel to these lines, as shown by the dotted lines *v'*, and in this way a reading is obtained.

Inclined-coil ammeters and voltmeters are made in a wide variety of styles suitable for switchboard work and also for work where portable instruments are needed. Fig. 41 shows the external appearance of a horizontal-edgewise type of inclined-coil ammeter.

Fig. 41

The edgewise type is now very largely used for switchboard work, as it occupies less space than the ordinary flat scale type and gives a form of scale that is very easily read. Fig. 42 shows the instrument with the cover removed; the dotted outline shows the location of the inclined coil. Commercial measuring instruments should, as far as possible, be dead beat, i. e., when deflected they should come to rest quickly. In order to dampen the movements of the pointer, a number of different methods are available. In the instrument shown in Fig. 42, the movements are dampened by an

FIG. 42

aluminum disk *a* that moves between the pole pieces of the permanent magnets *b*, *b*. The disk is mounted on the lower part of the shaft that carries the iron vane. As the disk moves between the magnet poles, eddy currents are generated in it, and the reaction of these currents on the magnetic field produces a retardation that effectually dampens the movements of the needle.

INDUCTION INSTRUMENTS

40. The Westinghouse alternating-current ammeter, shown in Figs. 43 and 44, is claimed to be accurate for different frequencies and for changes in temperature. It

consists of a laminated iron core *k* that has around one arm the actuating coil *c* through which the current flows. In parallel with this coil is a non-inductive resistance *h*, which is mounted where shown merely for convenience. The dif-

FIG. 49

ference of potential at the terminals of these coils will remain substantially constant for all frequencies; hence as the frequency increases, the coil *c* will take less and the resistance *h* more current. The periphery of the disk *f* has the form of a spiral; it projects into the air gap of the core *k* a maximum distance when the disk is at its zero position as a result of no current flowing through the coil *c*.

Mounted on each arm of the core *k* are two short-circuited coils *d*, *e*, one side of each coil being located in a slot in the core, so that the field due to current set up in these coils is displaced with reference to the field set up by the coil *c*, and inasmuch as the currents in coils *d*, *e* are produced by induction from the current in coil *c*, there will also be a displacement of phase and a shifting magnetic field will result. The alternating field set up when current flows through the coil *c* induces a current in the disk *f*, which is acted upon

by a secondary alternating field differing in phase from the first and due to the induced currents in the coils *d*, *e* by the

(*b*)

Fig. 44

original alternating field. The reaction of the current induced in the disk upon the secondary alternating field

tends to rotate the disk; this will be fully explained in connection with induction motors. As the current through coil *c* increases, the armature will be rotated; and as the radius of the disk becomes shorter, the degree to which the disk projects into the air gap will decrease, thus giving a more uniform scale than would be the case with a circular disk. The spiral spring *n* opposes the rotation of the disk, which is supported in jewel bearings and is very evenly balanced. A permanent magnet *m* makes the instrument dead-beat. The shunt resistance *h* should have a temperature coefficient at least as high as that of the disk, so that as the resistance of the disk increases with the temperature and the torque exerted upon it consequently tends to decrease, the shunt resistance will also become heated and will, therefore, take less current, thus forcing more current through the coil *c* to compensate for the effect of heat in the disk.

This type of instrument may be arranged to serve as a voltmeter and also as a wattmeter by the use of current and potential coils, as explained in connection with wattmeters.

ELECTRODYNAMOMETERS

41. The alternating-current instruments, which are perhaps the most widely used, belong to the third class. In the class known as **electrodynamometers**, the current in a swinging coil is acted on by a magnetic field produced by a fixed coil. The field produced by the fixed coil changes with the changes in the current, the arrangement being somewhat similar to that used in the Weston direct-current instrument, except that the permanent magnet producing a constant field is replaced by a fixed coil producing an alternating field. The Siemens dynamometer has already been described in a previous section. This instrument is largely used for standardizing purposes in laboratories, but it is not well suited to commercial work, because it is not direct reading, and also because it is not portable. An

electrodynamometer, if calibrated, with direct current, will indicate square-root-of-mean-square or effective values of alternating current.

42. For commercial work, it is necessary to have instruments that may be more readily worked with and handled

Fig. 45

than the Siemens electrodynamometer, and that will also have the advantage of being direct reading. The **Weston alternating-current voltmeter** is a good example of the

dynamometer principle as applied to a portable instrument. In this instrument the swinging coil is mounted between two fixed coils, and is carried on jewel bearings. The movements of the coil are counteracted by two small flat spiral springs, which also serve to carry the current into the coil; in fact, the whole construction is similar to that of the Weston direct-current instruments previously described, except that the magnetic field is produced by the two fixed coils instead of a permanent magnet. The instrument gives direct readings in volts by means of a pointer attached to the vertical pivot that carries the coil.

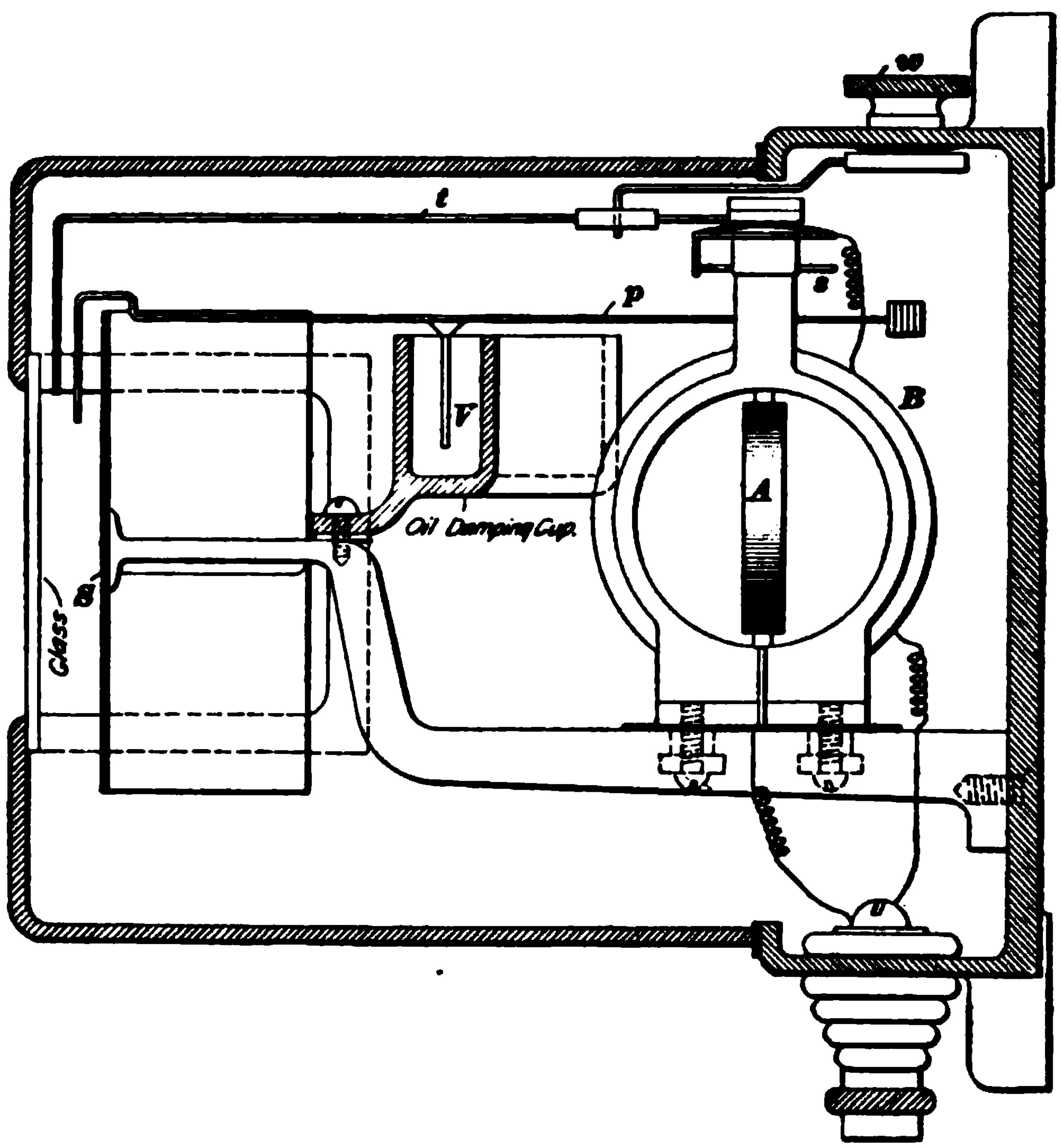


FIG. 46

43. Wagner Alternating-Current Voltmeter.—Fig. 45 shows two types of alternating-current voltmeter for switchboards made by the Wagner Electric Manufacturing Company; (*a*) shows the type used when the voltmeter is

mounted wholly on the front of the board; (*b*) shows the type where the working parts are in a case behind the board, the scale being illuminated from the rear by means of lamps. Fig. 46 shows the construction of the type shown in Fig. 45 (*a*); Fig. 47 shows the construction of the

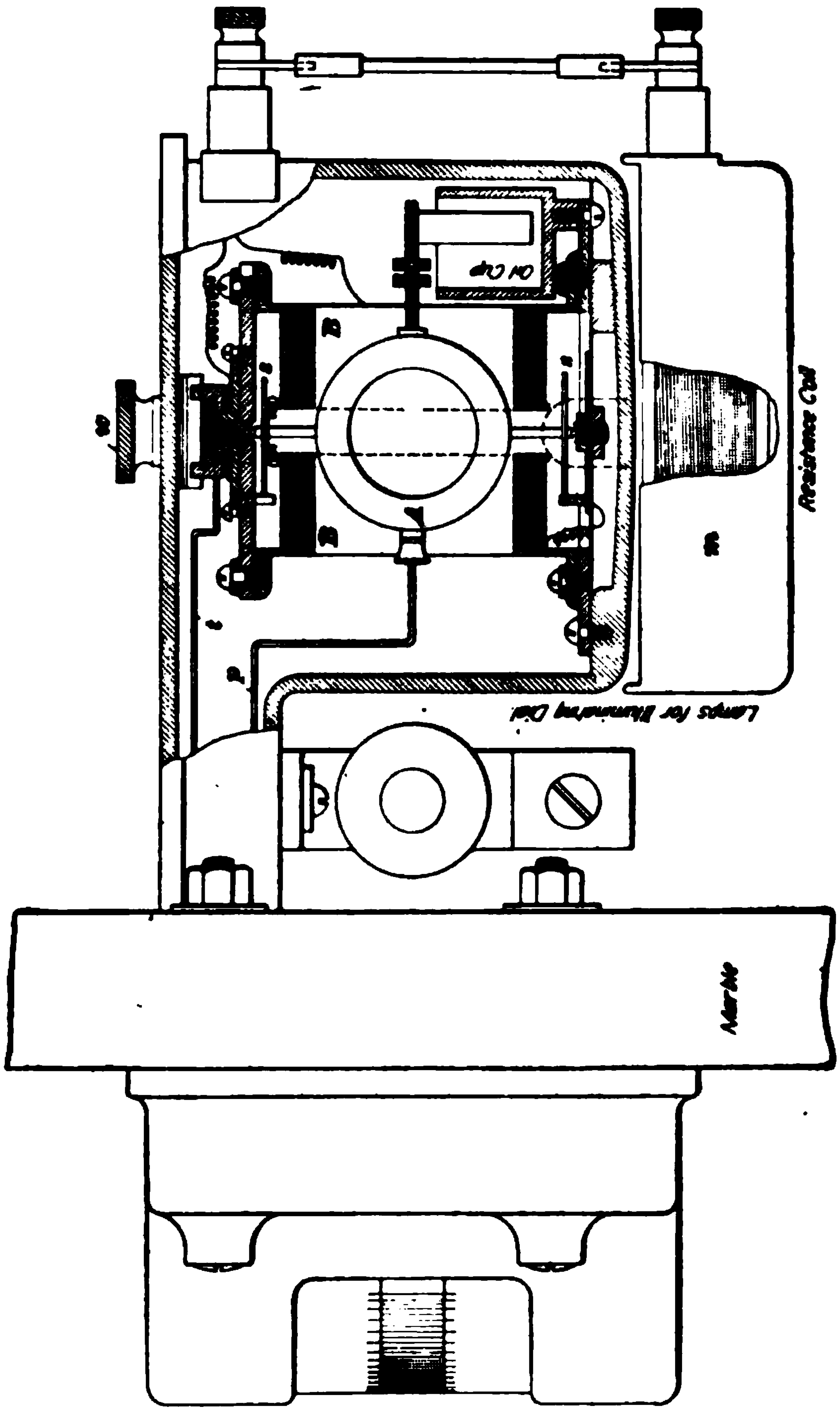


Fig. 47

voltmeter shown in Fig. 45 (*b*). In each case *A* is the swinging coil, and *B*, *B* the fixed coils. The swinging coil is delicately mounted on sapphire bearings, and its movement is counteracted by the small spiral springs *s*, *s*. The

pointer arm p carries the pointer that moves over the scale S, which forms a portion of a circular arc. In addition to the pointer arm, there is an index arm t that can be set at any desired point on the soale by means of the knob w. This index indicates the point at which the voltage should be kept so that any movement of the pointer on either side of the index is at once noted. In these instruments the movements of the pointer are very effectually damped by means of a small aluminum vane or tube V that moves to and fro in a cup containing oil. In Fig. 45 (b) and Fig. 47 the lower-case m contains the high resistance that is inserted in series with the voltmeter to limit the current flowing through the coils.

WATTMETERS

44. In order to measure the power supplied in an alternating-current circuit, we must have an instrument that will indicate the real watts expended, i. e., one that will give deflections proportional to $E I \cos \phi$. Such an instrument is called a **wattmeter,** and has been mentioned in the description of instruments used for direct-current measurements.

A wattmeter must average up all the instantaneous values of the product of current and E. M. F.; consequently, it must be so arranged that its indications will be affected by

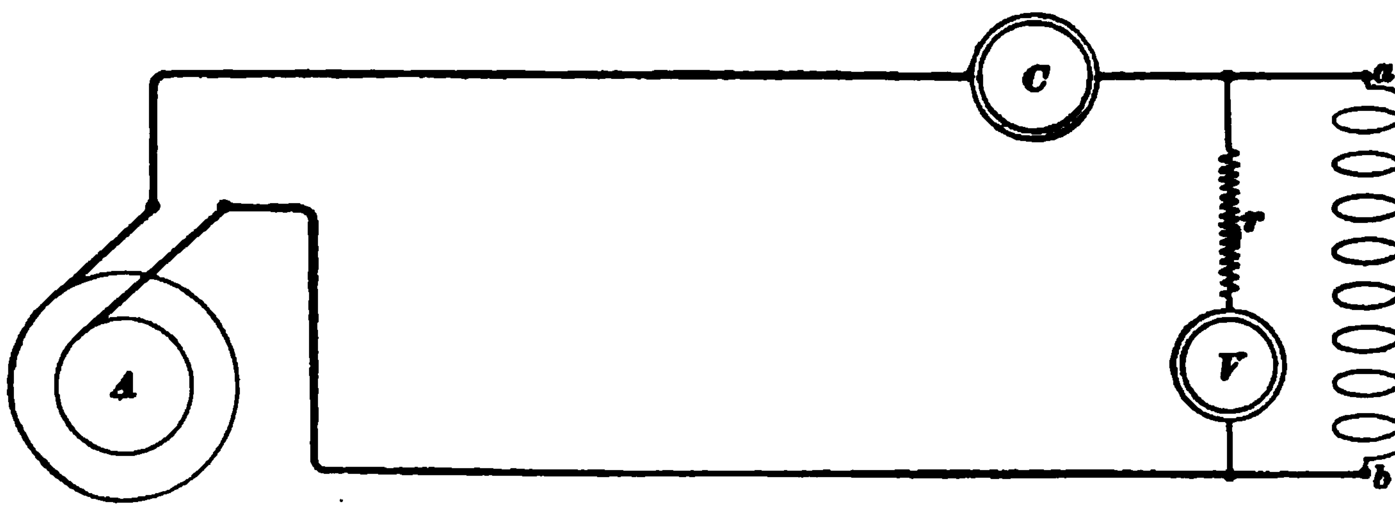


FIG. 48

both. The dynamometer can easily be adapted to this work by changing the winding and connections of the swinging coil. Consider a circuit $a b$, Fig. 48, in which energy is

being expended, and suppose for the present that it is connected to a direct-current dynamo. The watts expended may, in this case, be easily obtained by connecting an ammeter *C* in series with the circuit, and a voltmeter *V* across it, so as to get the values of the current and E. M. F., the product of which gives the required watts. This method would not work, however, if the circuit were connected to an alternator *A*, as shown in the figure, because it would take no account of the phase difference between current and E. M. F. In order to do this, it is necessary to combine the ammeter and voltmeter into one instrument. This is done by winding the fixed coil of a dynamometer with a few turns of heavy wire and connecting it in series with the circuit, while the swinging coil is wound with a large number of turns of fine wire and connected across the circuit. It is usual to connect a non-inductive resistance *r* in series with the swinging coil, in order to limit the current flowing in it. Since the resistance of the swinging-coil circuit is constant, the current flowing through it will, at all instants, be proportional to the E. M. F. acting on the circuit *a b*. The current in the fixed coil will also be equal to the current flowing in the circuit; hence, the torque action between the two coils will at each instant be proportional to the product $e\,i$, and the average torque action will be proportional to the average watts. Such an instrument will, therefore, indicate the true value of the watts expended, because it takes account of the phase difference between the current and E. M. F.

45. Portable Wattmeter.—The Siemens wattmeter, like the dynamometer, is not direct reading, and is, therefore, not as convenient for commercial work as the portable direct-reading types, such as the Weston. It is, however, the standard wattmeter, and the one that is used for calibrating other instruments, because, like the dynamometer, there are few parts about it to change or get out of order. Fig. 49 shows a **Weston portable wattmeter.** This is constructed about the same as the voltmeter, except that

the fixed coils are composed of a few turns of heavy copper conductor that carry the current. The heavy binding posts *a*, *b* at the side of the case are the terminals of these current coils, and the small binding posts *c*, *d* on the top connect with the swinging coil. In using wattmeters, care should be taken not to get the connections mixed, because if the current coil should, by mistake, be connected across the circuit, the instrument

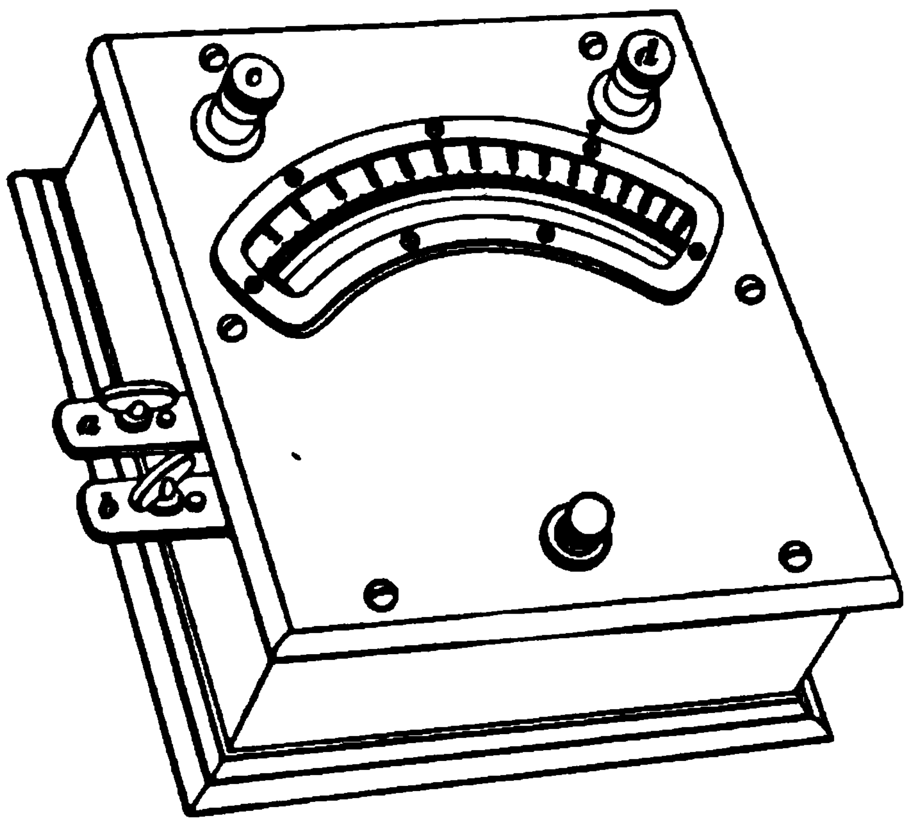


FIG. 49

would in all probability be burned out, as the resistance of this coil is very low and the resulting current would be enormous. In order that the readings of a wattmeter may be reliable, the self-induction of the swinging coil should be very small. This is especially necessary if the instrument is to be used on a number of circuits having different frequencies. If the self-induction is high, the instrument will not read correctly for any other frequency than the one with which it was calibrated. The bad effect of the self-induction of the movable coil can, however, be made of negligible amount by using a very high non-inductive resistance *r*, Fig. 48, in series with the coil. If this is done, the impedance of the fine-wire circuit becomes so nearly equal to the resistance that the current in the swinging coil becomes so nearly in phase with the E. M. F. that the readings of the wattmeter are practically correct.

46. Compensated Wattmeter.—In Fig. 48 it will be seen that the current in *C* is the sum of the currents in *a b* and *V*. A wattmeter with its current and potential coils connected as shown would indicate a number of watts in

excess of the number expended in *a b*, because the effect of the series-coil is larger than it would be if the current in the circuit *a b* alone were passing through it. Of course, the current in *r* and *V* is very small, and if the current in *a b* is at all large, the error so introduced does not amount to much; but if the current in *a b* is small, the error might be appreciable. In the **Weston compensated wattmeter**, the wire connecting to the swinging coil circuit is laid alongside the turns of the coarse-wire coils, and is so connected that the current in the fine wire flows in a direction opposite to that in the coarse wire. The excess of current in the coarse-wire coil is, therefore, offset by the counter-magnetizing action of the fine-wire turns, and the instrument indicates the watts expended in the circuit or device to which the wattmeter is connected.

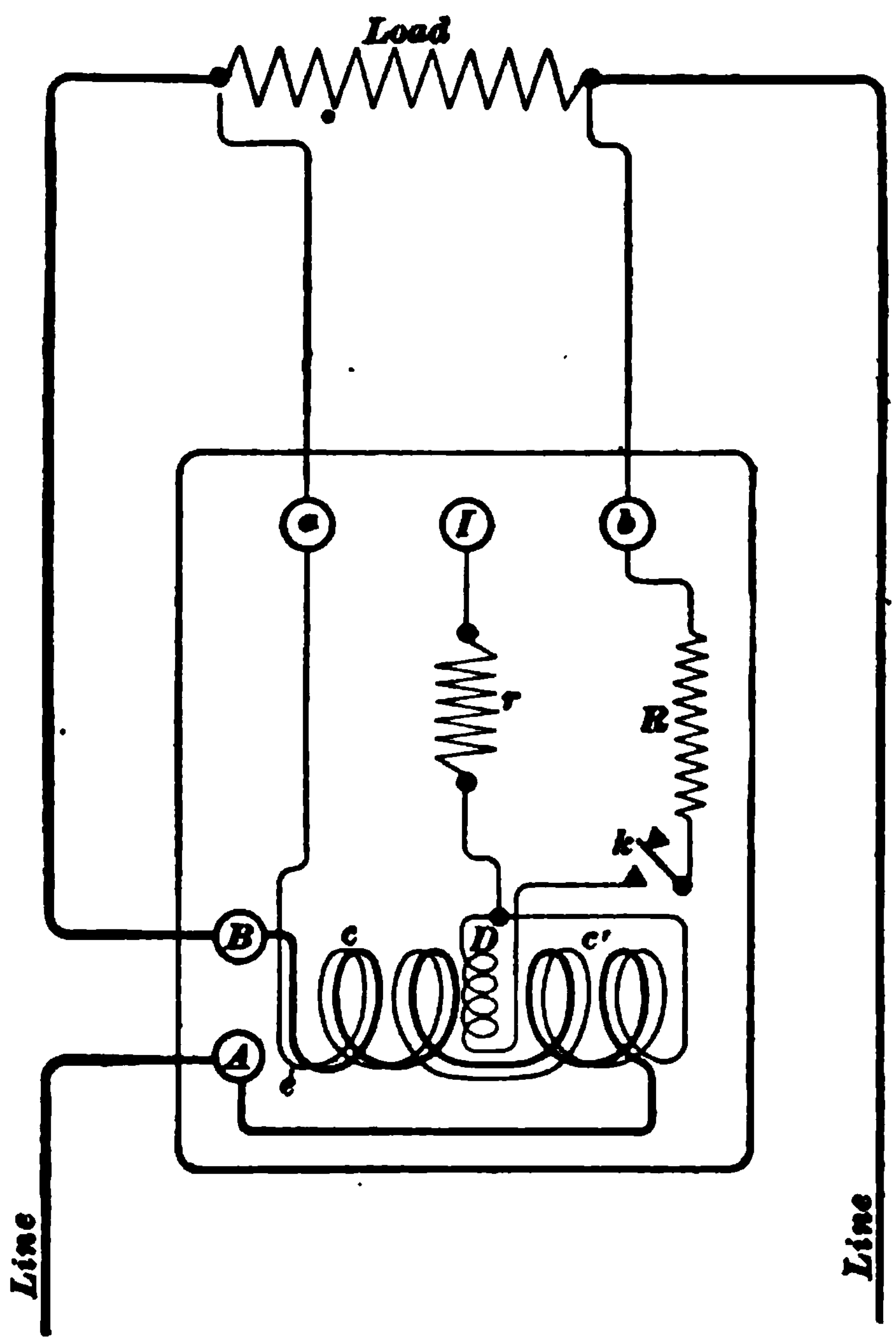


FIG. 50

Fig. 50 shows the connections of the instrument. *A* and *B* are the current terminals connected to the current coils *c*, *c'*. The compensating coil *e* is connected in series with the swinging coil *D*, and the protective resistance *R*. The potential binding posts that are ordinarily used for measuring the power supplied to a given load are *a b*. When a reading is taken, the button *k* is pressed, thus allowing current to pass through the swinging coil. A third binding post *I* is provided for use when the field

and pressure terminals are connected to independent circuits. Such connections are required when the instrument is being checked by passing a current through the current coils and applying a variable pressure to the potential coil; also, in cases where a test is being made with a constant current and varying pressure. In case an independent potential circuit is used in this way, the potential terminals are connected to posts $I b$, thus cutting out the compensating coil. The small resistance r takes the place of coil e, so that the resistance of the potential circuit remains unaltered. The wattmeter shown in Fig. 49 is not provided with a compensating coil; hence, the middle binding post I is not provided. Wattmeters are made in a large variety of forms both for switchboard and portable work, and can be obtained to cover almost any desired range.

47. Thomson Inclined-Coil Indicating Wattmeter. Fig. 51 shows a Thomson inclined-coil, horizontal-edgewise, indicating wattmeter as used by the General Electric Company on alternating-current switchboards. Its construction is practically the same as the inclined-coil instrument shown

FIG. 51

in Fig. 42 except that the small iron vane is replaced by a coil of fine wire mounted at an angle to the shaft. The fixed coil A carries the main current, and is wound with a few turns of copper strip. This coil connects to the current studs B. The potential circuit connects to the upper

studs C, and current is carried into the swinging coil by means of small spiral springs in the usual manner. The protective resistance in series with the swinging coil is usually mounted separately on the back of the switchboard.

48. Wagner Indicating Wattmeter.—The Wagner indicating wattmeters are constructed in the same manner as the voltmeters shown in Figs. 46 and 47. The only difference is that the stationary coils are provided with a few turns of heavy conductor and are connected in series with the circuit, while the swinging coil, in series with its resistance, is connected across the circuit. In the voltmeter, the armature and field coils are each wound with fine wire, and are connected in series with each other.

Wattmeters of the electrodynamometer type are made in many different forms, but they all involve the same principle, though the disposition of the current and potential coils may vary in different instruments. In the Stanley wattmeters the coils are made approximately spherical in shape. In proportioning the coils and fixing their disposition as regards each other, the object aimed at is to secure as even a scale as possible, i. e., to prevent the divisions from being crowded together at either end of the scale.

49. Sometimes it is necessary to know the total amount of energy expended in a circuit during a given interval of time, as, for example, in measuring the output of a station or the energy supplied to a consumer. For this purpose it is necessary to use a *recording wattmeter*, i. e., an instrument that will record the number of watt-hours electrical energy supplied during a given period. One of the commonest types of such an instrument is the Thomson recording wattmeter, already described. This is really a modified Siemens wattmeter, arranged so that the moving coil revolves so long as current is passing. Recording wattmeters are made in a large variety of styles and sizes, and information relating to their use will be given later in connection with the applications of alternating currents to power transmission.

ELECTROSTATIC VOLTMETERS

50. Another class of voltmeter available for alternating-current work is that which depends on the repulsion or attraction of two surfaces carrying electrostatic charges. Such instruments have been used most largely in commercial work for measuring high voltages, but instruments are also made on this principle that are quite capable of measuring low voltages. One type used for measuring

FIG. 52

high potentials is that invented by Lord Kelvin, and illustrated in Fig. 52. A set of fixed quadrants a, a', b, b' is mounted so that the aluminum vane $v\,v'$ may swing between them on the pivot d. The fixed set of quadrants is connected to one side of the circuit and the swinging vane to the other, so that when they become charged, the vane is attracted and drawn in between the quadrants, and the voltage is indicated by the pointer. These voltmeters have

the advantage that they require no power whatever for their operation. This is sometimes of importance, especially when the instrument is connected to a high-potential circuit and left connected continuously. A very small current in such a case might represent a considerable loss of energy.

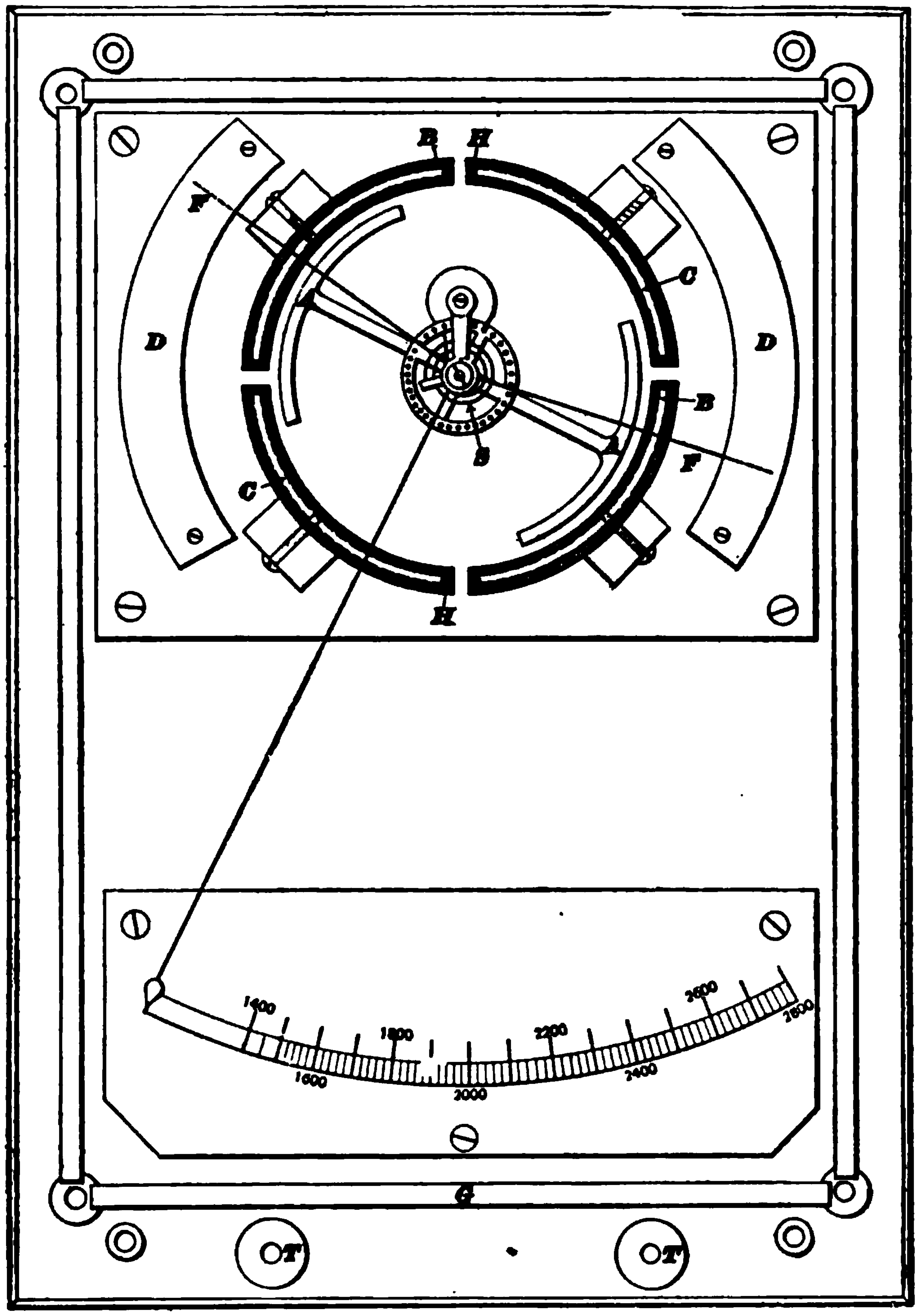


FIG. 53

51. Stanley Electrostatic Voltmeter.—Fig. 53 shows a type of electrostatic voltmeter used by the Stanley Electric

Manufacturing Company on alternating-current switchboards. It operates on the same principle as the voltmeter shown in Fig. 52, but the general arrangement is different. *B*, *B* and *C*, *C* are fixed plates mounted on a hard-rubber base. These plates are protected by a hard-rubber covering *H* to prevent leakage and also to obviate any danger of short-circuiting between the vanes. *A* is a movable aluminum vane, to which is attached the pointer, the movement of which is counterbalanced by the spiral spring *S*. The fixed plates *B*, *B* and the movable vane *A* are connected together and form one pole of the instrument. The fixed plates *C*, *C* are connected together and form the other pole. When the voltmeter is connected to the circuit, *B* and *A* being charged alike will repel each other, while at the same time *C* and *A* will attract each other, with the result that the vane is deflected an amount depending on the pressure of the circuit. Two plug receptacles *T*, *T* are provided on the instrument, in addition to the regular terminals, so that it may be compared at any time with a standard instrument. The movement of the needle is damped or steadied by the vanes *F* moving in the partially closed boxes *D*.

Other types of electrostatic instruments are made, but they all work on about the same principle. The electrostatic ground detector, described later in connection with switchboard appliances, is constructed in practically the same manner as the electrostatic voltmeter.

ALTERNATORS

SINGLE-PHASE ALTERNATORS

GENERAL CHARACTERISTICS

1. Dynamo-electric machines used for the generation of alternating E. M. F.'s are known as **alternators.** It has already been shown that the E. M. F. generated in the armature of a direct-current dynamo is essentially alternating, and that the commutator is supplied to change the connections of the external circuit so that the current in it may be direct. It follows, therefore, that if the proper terminals of a continuous-current armature were connected to two collector rings in place of a commutator, the current furnished would be alternating. In the majority of cases, however, alternator armatures are not wound in the same way as those for direct current. Consider a horseshoe electromagnet as shown in Fig. 1. When such a magnet is excited by means

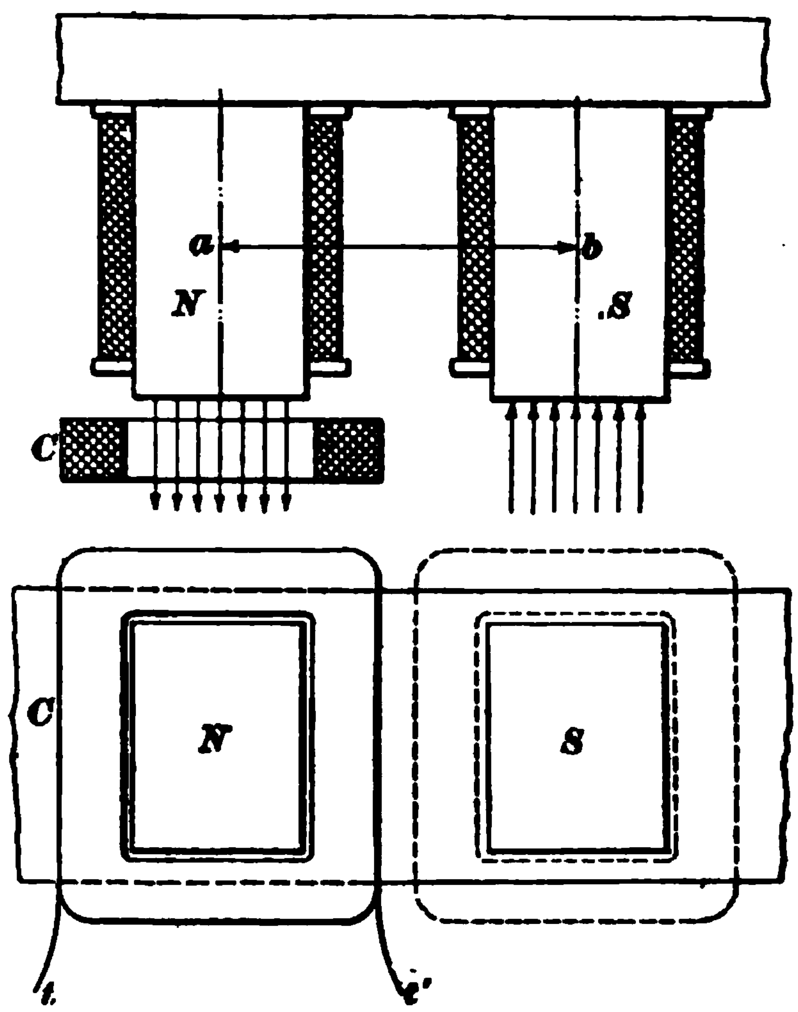


FIG. 1

of the coils on its two limbs, lines of force will flow out of the north pole N into the south pole S, as indicated by the arrows. The two pole faces are shown in the lower diagram, and the rectangular coil of wire C is supposed to be moved across the pole face N to the position shown by the dotted outline in front of S. When the coil is in the position shown under the north pole, a small movement of the coil to the right will not cause a very large change in the number of lines threading it; consequently, only a small E. M. F. will be induced. While the conductors are moving under the pole pieces, the E. M. F. will be practically uniform if the field is uniform, and when the coil has reached the position shown by the dotted line, the E. M. F. will again be zero. The E. M. F. has, therefore, passed through one alternation, or half cycle, while the coil has been moved through the distance $a\,b$. This E. M. F. curve may be of the shape shown in Fig. 2, the portion at y being fairly uniform while the conductors are moving under the poles; or it may have a different shape, depending on the shape of the coil and pole pieces as well as on the way in which the magnetic lines are distributed.

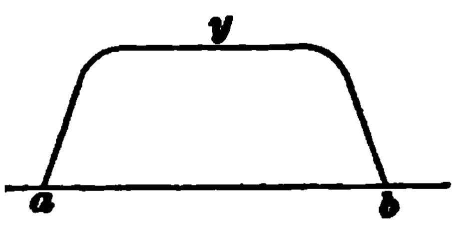


FIG. 2

No matter what the shape of the curve $a\,y\,b$ may be, the E. M. F. passes through one alternation when the coil is moved a distance equal to that from the center of one pole to the center of the next. If the coil C be moved back from S to N, the same set of values of the E. M. F. is generated in the opposite direction; hence, by moving the coil from N to S and back, the E. M. F. passes through one complete cycle, as shown in Fig. 3. The arrangement shown in Fig. 1 would, therefore, constitute an elementary alternator, and the E. M. F. would be set up by movements of the coil back and forth across the pole faces, there being no rotation at all. Instead of moving the coil back and

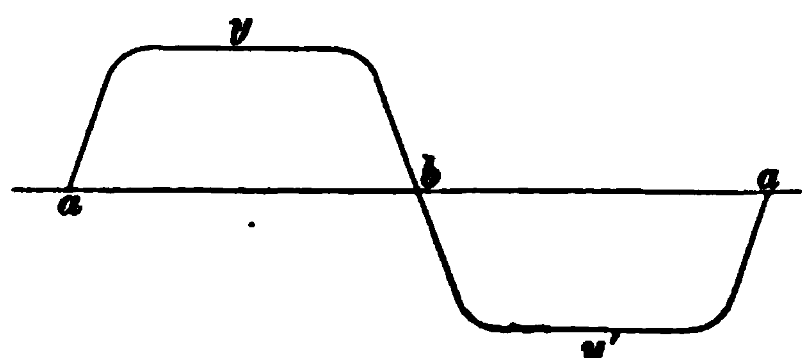


FIG. 3

forth, the same effect could be produced by moving the coil forwards continuously in front of a row of poles, as shown in Fig. 4. As the coil C moves past the poles, it cuts the lines of force first in one direction and then in the other, thus producing the alternating E. M. F. represented by the curve below. It should be noted that while the coil moves through the distance between one north pole and the next pole of the same polarity, the E. M. F. passes through one complete cycle. The distance from a to c, therefore, corresponds to 360° on the E. M. F. curve, and $a\,b$ to 180°. For every pair of poles passed, the E. M. F. passes through a

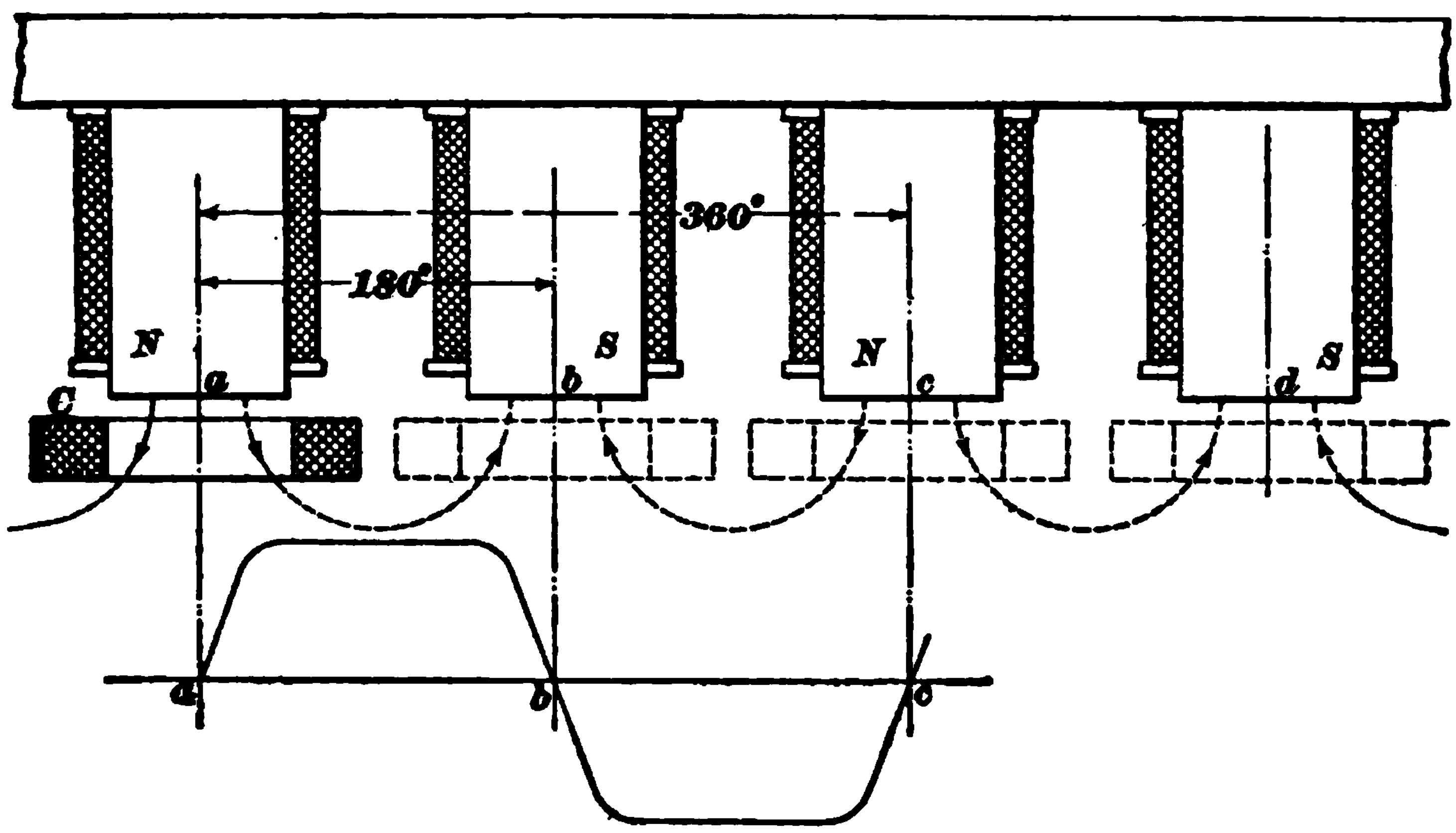


FIG. 4

complete cycle of values; hence, it follows that the number of cycles per second, or the frequency of an alternator, is equal to the number of pairs of poles that the armature winding passes per second. If the number of poles on the machine is p, the number of pairs of poles is $\frac{p}{2}$, and if the coil is moved past the poles s' times per second, the frequency n will be

$$n = \frac{p}{2} s' \qquad \textbf{(1)}$$

2. Instead of the single coil *C*, Fig. 4, being used by itself, three other coils, shown dotted, might be connected in series or parallel with *C*, and the whole four moved together in front of the poles. If the coils were connected in series, it is evident that the total E. M. F. produced would be increased, because all the E. M. F.'s generated in the turns of the different coils would be added up. If they were connected in parallel, the E. M. F. would be the same as that produced by the single coil, but the current-carrying capacity would be increased, because there would now be four circuits to carry the current in place of one. It should be noted particularly that no matter how many coils there are, or how they are connected together, the frequency remains the same so long as the speed *s* and the number of poles is constant. In other words, the frequency of an alternator does not depend on the way in which the armature is wound. Connecting the coils in series is equivalent to making the winding of one coil of a large number of turns; connecting them in parallel amounts to the same thing as winding in one coil with a heavy conductor. As long, therefore, as the coils are all moved simultaneously, as is always the case, the frequency is not affected in any way by the scheme adopted for winding and connecting up the armature.

3. It is evident that an alternating E. M. F. would be set up in the coil or set of coils, Fig. 4, if the magnet were moved and the coils held stationary. Also, both coils and magnet might be stationary and an E. M. F. still be induced by causing the lines of force threading the coils to vary. These three methods give rise to the following three classes of alternators:

1. Those in which the armature coils are moved relative to the field magnet.
2. Those in which the field is moved relative to a fixed armature.
3. Those in which the magnetic flux passing through a fixed set of coils is made to vary by moving masses of iron, called *inductors*, past them.

For convenience in referring to alternators, we will suppose that the armature is the revolving part and the field fixed, though it must be remembered that actual machines may be built with any of the three arrangements mentioned above.

CONSTRUCTION OF ALTERNATORS

4. The earlier type of alternator is that in which the coils are mounted on a drum and revolved in front of a magnet consisting of a number of radial poles. Alternator

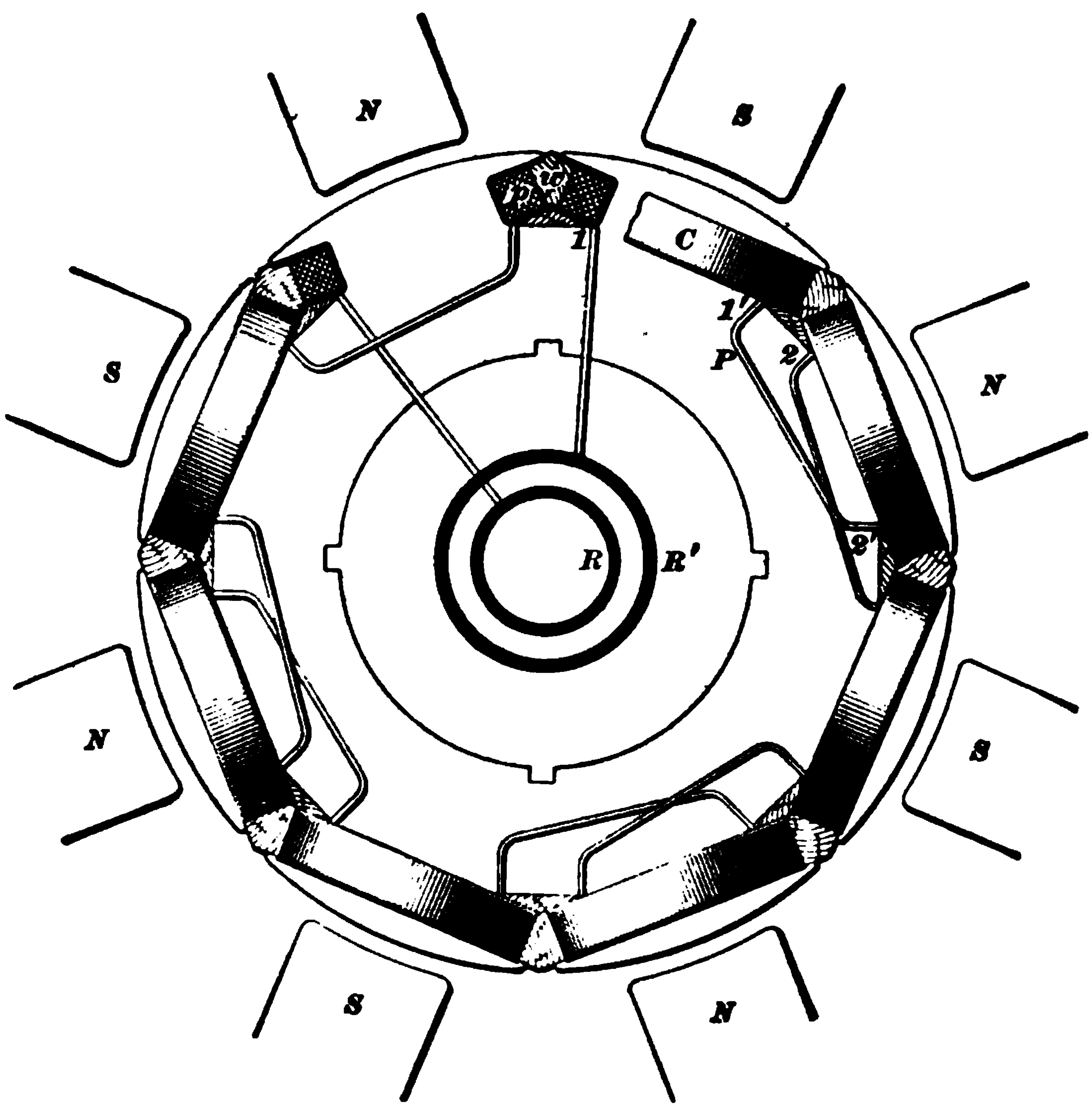


FIG. 5

armatures may be of the ring, drum, or disk type, but the drum style is used almost exclusively in America. If we suppose the poles, Fig. 4, bent into a circle and the coils

mounted on a drum revolving within the poles, we will have one of the earlier types of alternator. This arrangement is shown in Fig. 5, except that in this case the machine is provided with eight radial poles and eight coils on the armature, giving a style of winding in common use for machines used on lighting circuits. In this case, there are as many coils on the armature as there are poles on the machine; but a winding might easily be used in which there would be only half as many coils as poles. There is a large variety of windings suitable for alternators, and the designer must select the one best suited to the work that the machine must do. In Fig. 5, the coils *C* are shown bedded in the slots *p* on the circumference of the iron core *P*, which is built up of thin iron stampings. These coils are heavily taped and insulated and are secured in place by hardwood wedges *w*. This makes a style of armature not easily injured, and the use of the dovetailed slots and wooden wedges does away with the necessity of band wires. As the armature revolves, the coils sweep past the pole faces, and the E. M. F. is generated in the same way as in Fig. 4; i. e., the movement of the coils relative to the pole pieces becomes one of translation rather than of rotation.

5. Alternators are generally required to furnish a high voltage, and, in consequence, the armature coils are usually connected in series. Care must be taken in connecting up such windings to see that the coils are so connected that none of the E. M. F.'s oppose one another. By laying out a diagram of the winding, the manner in which the coils must be connected will be easily seen. This has been done in Fig. 6, which shows diagrammatically the winding of the armature in Fig. 5. The coils are represented by the heavy sector-shaped figures, and the connections between them by the lighter lines. The circles in the center represent the collector rings of the machine, and the radial lines that part of the coil which lies in the slot, that is, the part in which the E. M. F. is generated. The circular arcs joining the ends of the radial lines represent the ends of the coils that project

beyond the laminated armature core. The drawing is made to show the coils at the instant the conductors in the slots are opposite the centers of the pole pieces. At this instant the E. M. F. will be assumed to be at its maximum value and that the direction of rotation is such that the conductors under the north poles have their E. M. F.'s directed

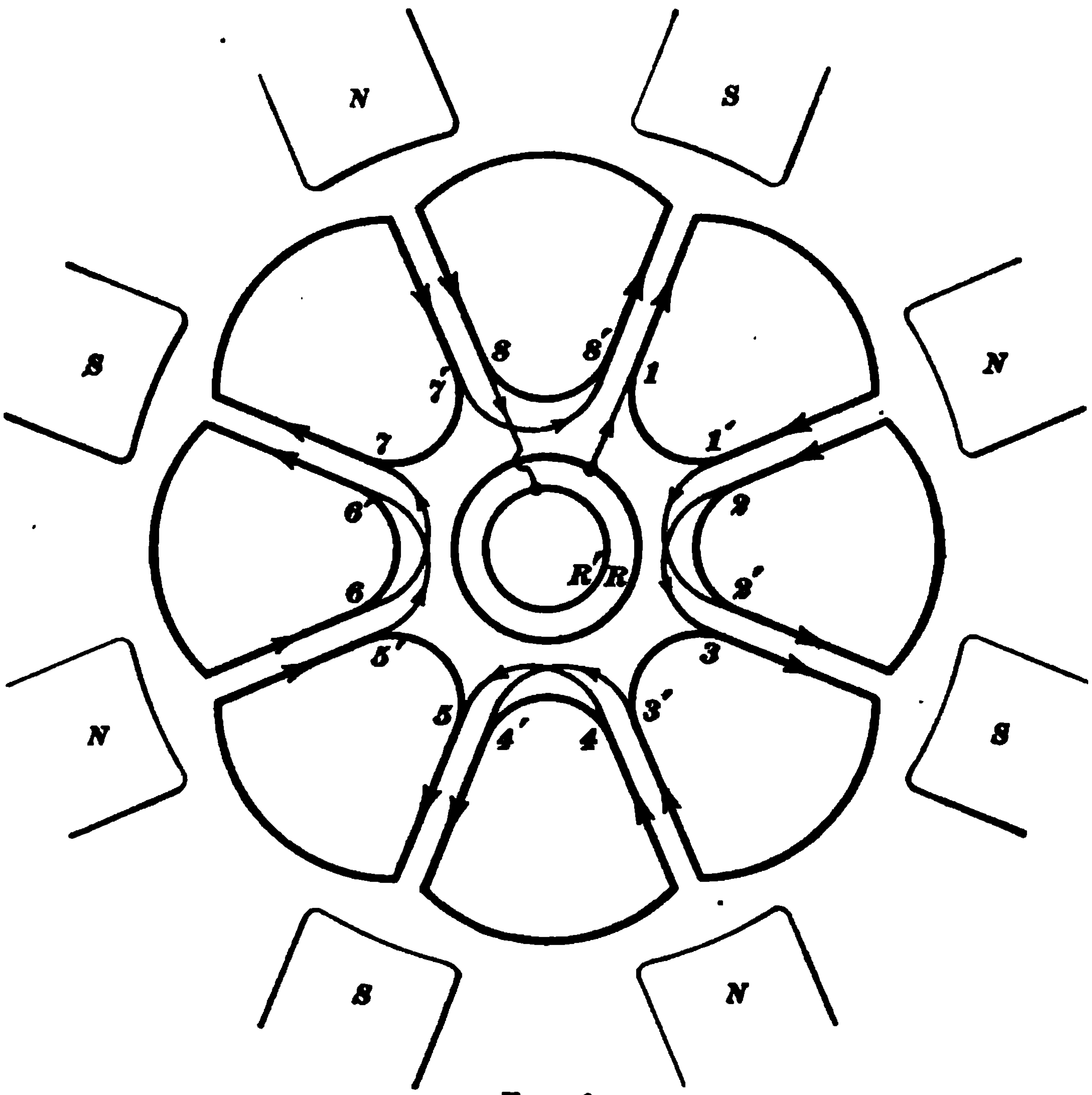


FIG. 6

from the back of the armature toward the front. These E. M. F.'s will be denoted by an arrowhead pointing toward the center of the circle, since the inner end of the radial lines represents the front or collector-ring end of the armature. The E. M. F.'s in the conductors under the south poles must be in the opposite direction, or pointing away from the center. After having marked the direction of these E. M. F.'s, it only remains to connect the coils so that the

current will flow in accordance with the arrows. Starting from the collector ring *R*, and passing through the coils in the direction of the arrows, it is seen that the connections of every other coil must be reversed; i. e., if *1*, *1'*, *2*, *2'*, etc., represent the terminals of the coils, *1'* and *2'* must be connected together, also *2* and *3*, and so on. The end *8* is connected to the other collector ring and the winding thus completed. The connections of such a winding are quite simple; but if not connected with regard to the direction of the E. M. F.'s, as shown above, the armature will fail to work properly. For example, if *1'* were connected to *2*, *2'* to *3*, and so on around the armature, the even-numbered coils would exactly counterbalance the odd-numbered ones, and no voltage would be obtained between the collector rings. Of course, in this case all the coils are supposed to be wound in the same direction, as is nearly always done in practice. The connections shown in the diagram, Fig. 6, are shown between the coils in Fig. 5. It should be noted, in passing, that this constitutes an open-circuit winding; that is, the winding is not closed on itself, like that of a continuous-current drum or ring armature. A large number of alternator windings are of the open-circuit type, which is better adapted for the production of high voltages, because it admits of a large number of turns being connected in series.

6. Most alternating-current dynamos of the revolving-armature and stationary-field type are built on much the same lines as direct-current multipolar machines. Usually, however, they have a larger number of poles. Fig. 7 shows a Fort Wayne (Wood) alternator with revolving armature and stationary field with inwardly projecting poles. This is an eight-pole machine with an armature winding similar to that shown in the diagram, Fig. 6, and represents a type of machine largely used for lighting work. The two collector rings *r*, *r* are seen mounted on the shaft inside the bearing, and are connected to the armature winding by heavily insulated leads *n*, *n*. The terminals of the machine are at *t*, *t'*

and leads o, o' connect to the shunt across the series field coils, as explained later. The *commutator*, or *rectifier*, is shown at m and is used to commutate the current passing around the series field coils. The exciter is in this case driven from the alternator shaft. Fig. 7 is typical of belt-driven revolving-armature alternators. In some makes, the commutator or collector rings are placed outside the bearing and the connections brought through a hole in the shaft. This allows the bearings to be placed closer together, but it makes the insulation more difficult and it is questionable whether there is any advantage in it.

Fig. 8 shows a Westinghouse alternator with revolving armature designed for a low speed (150 revolutions per minute) in order to allow direct connection to a waterwheel. The machine is of 650 kilowatts capacity, and is provided with 4 collector rings because the armature has a two-phase winding.

7. The number of poles on these machines is made large, in order to obtain the necessary frequency without running the machine at too high a speed. It is evident from what has been pointed out that for every revolution of the armature the E. M. F. passes through as many complete cycles as there are pairs of poles, and the frequency must be $n = \frac{p}{2} s$, where p was the number of poles and s the number of revolutions of the armature per second.

Since
$$n = \frac{p}{2} s \qquad (2)$$
or
$$s = \frac{2n}{p} \qquad (3)$$

Therefore, with a given frequency n, the number of poles must be made large if the speed s is to be kept down. For example, if an alternator has 8 poles and runs at a speed of 900 revolutions per minute, its frequency will be $\frac{8}{2} \times \frac{900}{60}$ $= 60$ cycles per second. If we attempted to obtain a

frequency of 60, which is a very common one, by using a two-pole machine, the speed would have to be $s = \frac{60}{1}$, or 60 revolutions per second, or 3,600 revolutions per minute, a speed altogether too high for a machine of any size.

FIG. 8

8. It follows from the above that if the frequency is fixed, as it usually is, and it is desired to run an alternator at a given speed, it must be made with such a number of poles p that the condition $n = \frac{p}{2}s$ will be fulfilled. Alternators are often required to run at a specified speed in cases where they are to be coupled directly to waterwheels or engines.

This leads to the designing of a large number of special machines suited to these conditions, because alternators, on account of the relation that must be preserved between frequency, speed, and number of poles, cannot be adapted to different conditions of speed and voltage by changing the armature winding, as is done with direct-current machinery. The number of poles used on commercial machines varies greatly, as there is a wide range of frequencies and speeds to be met. Alternators are built with the number of poles varying all the way from 4 up to 60 or 80 and sometimes more. The number of poles usually increases with the size of the machine, because the speed of the larger dynamos is necessarily less than that of the smaller. For example, one Westinghouse 1,200-kilowatt alternator designed for direct connection to a steam engine has 40 poles and runs at a speed of 180 revolutions per minute, thus delivering current at 60 cycles. The number of poles, the output, and speed of some smaller sized machines are given below.

TABLE I

ALTERNATORS

Number of Poles	60 Cycle		Number of Poles	125 Cycle	
	Output Kilowatt	Speed R. P. M.		Output Kilowatts	Speed R. P. M.
8	75	900	10	30	1,500
12	150	600	14	120	1,070
16	250	450	16	200	940

9. The E. M. F. curve furnished by an alternator of the type shown in Fig. 7 would not follow the sine law. Such machines, with heavy coils embedded in slots, usually give a curve that is more or less peaked and ragged in outline, and are best adapted for lighting work. For purposes of power transmission, it is desirable to have a machine giving a

smooth E. M. F. wave, and this can be obtained by adopting the proper kind of winding for the armature. The advantages and disadvantages of the different windings will be taken up in connection with alternator design, attention being paid here to the principles governing the generation of the E. M. F. and the connecting up of the armature coils.

10. The distance ef, Fig. 9, from the center of one pole piece to the center of the next is called the **pitch** of the alternator. The relation between the pitch and the width of pole face A varies in different makes of machines, but in a large number of American alternators the distance B between the poles is made equal to the width of pole face A or one-half of the pitch, and the pole pieces cover 50 per cent. of the armature. The shape of the E. M. F. curve is determined largely by the relative shape of the coils and pole pieces and the way in which the conductors are disposed on the surface of the armature.

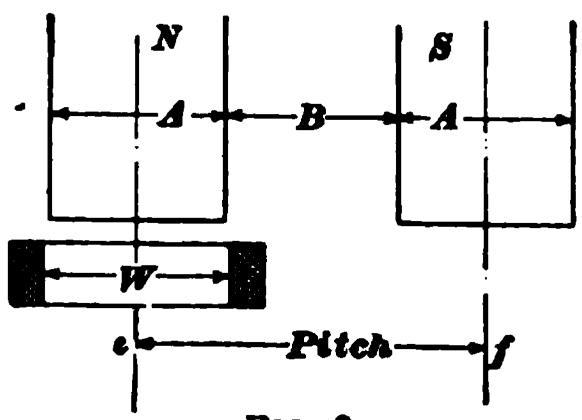


FIG. 9

The width of the opening W in the coil should not, in general, be much less than the breadth of the pole piece A. It has been found that it may be slightly less without doing any harm; but if made too narrow, trouble is likely to arise owing to the E. M. F.'s induced in different conductors of the same coil being opposed to one another, thus cutting down the total E. M. F. generated.

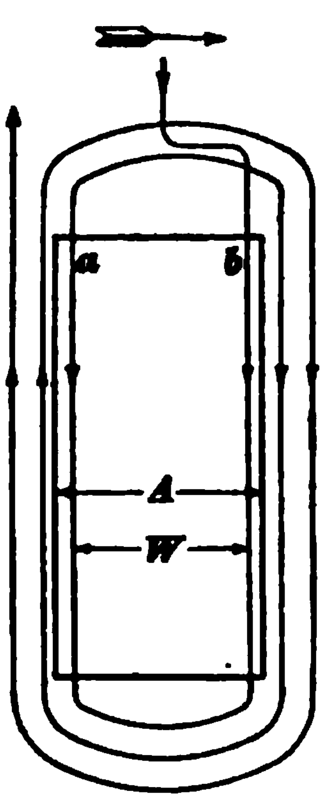


FIG. 10

This will be seen by referring to Fig. 10, where a coil of three turns is shown with its width of opening W less than the polar width A. When the coil moves across the pole face in the direction of the arrow, the E. M. F.'s induced

in the two conductors a and b will be in the same direction, because they both cut lines of force in the same way. The consequence is that these two E. M. F.'s oppose each other, as will be readily seen by following the arrowheads. When an alternator is loaded, the armature reaction causes the magnetism to crowd more or less toward one side of the poles, thus practically reducing the width of the magnetic flux, and on account of this it has been found possible to make the width W a little less than A without bad results. Usually, however, the width of the opening is nearly equal to that of the pole face.

CALCULATION OF E. M. F. GENERATED BY ALTERNATORS

11. It has been shown that the effective E. M. F. induced in a coil, when a magnetic flux Φ is made to vary through it according to the sine law, is

$$E = \frac{4.44\,\Phi\,T\,n}{10^8}$$

This is the case in an alternator producing a sine E. M. F. The flux Φ, which is caused to vary through the coils by the motion of the armature, is the number of lines flowing from one pole piece; T is the total number of turns connected in series on the armature; and n is the frequency. This formula may be easily proved by remembering that the average volts equals the average number of lines of force cut per second divided by 10^8.

Let s = revolutions per second;
p = number of poles;
Φ = number of lines flowing from one pole;
T = number of turns in series;
$2T$ = number of conductors in series.

Each conductor cuts an average of $p\,\Phi$ lines per revolution, or $p\,\Phi\,s$ lines per second; hence,

$$\text{average E. M. F.} = \frac{p\,\Phi\,s \times 2\,T}{10^8} = \frac{2\,\Phi\,T\,p\,s}{10^8}$$

But $$p \times s = 2\,n$$

hence, $$\text{average E. M. F.} = \frac{4\,\Phi\,T\,n}{10^8}$$

The effective E. M. F. is 1.11 times the average; therefore,

$$E = \frac{4\,\Phi\,T\,n \times 1.11}{10^8} = \frac{4.44\,\Phi\,T\,n}{10^8} \qquad (4)$$

or, the effective E. M. F. generated by an alternator is equal to 4.44 times the product of the number of lines flowing from one pole, the number of turns connected in series, and the frequency, divided by 10^8.

12. Formula **4** gives the effective E. M. F. at the collector rings when the alternator is run without any load, i. e., on open circuit. If the machine be loaded, the E. M. F. at the terminals will fall off from the value given by the above equation. This formula gives the total effective E. M. F. generated only when the turns T connected in series are so situated as to be simultaneously affected by the changes in the magnetic flux. This means that the conductors must be bunched together into heavy coils, like those shown in Fig. 5, if the maximum effect is to be obtained. If the winding were spread over the surface of the drum, as is done in direct-current armatures, the E. M. F. in one set of conductors would not rise to its maximum value until after the E. M. F. in the preceding set. For example, suppose we have an alternator wound with flat pancake coils, as shown in Fig. 11. The coil is here spread out to a certain extent, and the E. M. F.'s in the different turns will be slightly out of phase with each other, because they will not all come into and go out of action at the same instant. The total E. M. F. generated by such a coil will be the

resultant sum of the E. M. F.'s generated in the different turns, and the more these separate E. M. F.'s are thrown out of phase by spreading out the coil, the smaller will be the resultant terminal E. M. F. obtained. If the five turns of the coil shown in Fig. 11 were placed together in a slot, they would all be affected by the magnetic flux at practically the same instant. Hence, for a given length of

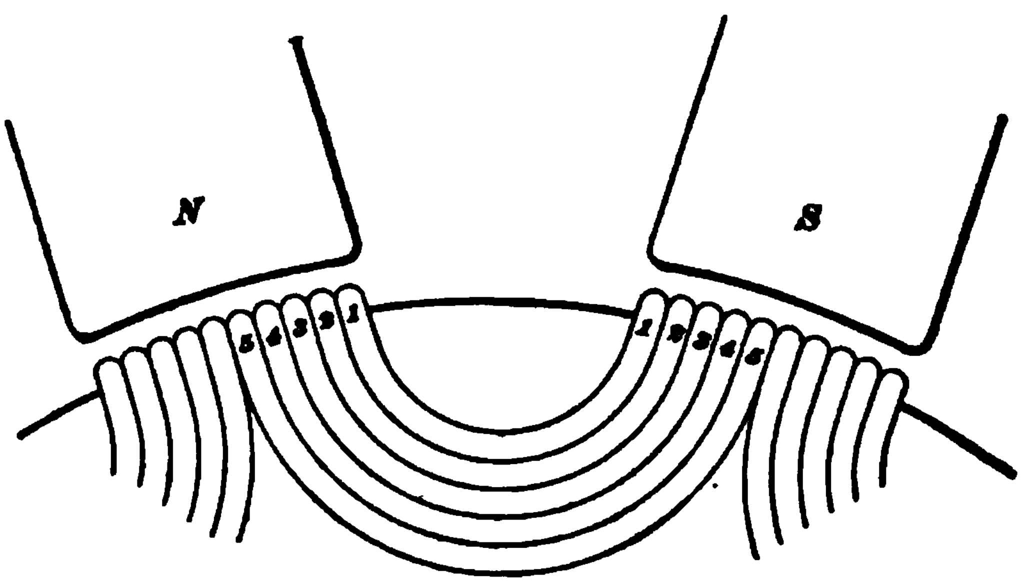


FIG. 11

active armature conductor, concentrated windings produce the maximum E. M. F. at no load, and if the winding is distributed, the terminal E. M. F. at no load is lowered. Both kinds of winding have their advantages and disadvantages, which will be taken up in connection with alternator design. For the present, the student will bear in mind that formula **4** gives the E M. F. when the machine is running on open circuit and when the winding is so concentrated that all the conductors pass into and out of action simultaneously.

13. The E. M. F. obtained at the terminals or collector rings of the alternator may be considerably less than that given by formula **4** when the machine is loaded, because a portion of the E. M. F. generated will be used in forcing the current through the armature against its resistance, and some of the E. M. F. will also be necessary to overcome the self-induction. In the case of a direct-current

dynamo, the pressure obtained at the brushes for any given load is equal to the total pressure generated less the pressure necessary to overcome the resistance of the armature. If I is the current and R the armature resistance, the lost volts are RI, and the pressure at the brushes is $E_b = E - RI$, where E is the total voltage generated. In the case of an alternator, the voltage at the terminals may fall off greatly as the load is increased, on account of the armature self-induction and also on account of the demagnetizing effect of the armature on the field, the falling off being much greater than that accounted for by the resistance. The effects of armature self-induction will best be understood by referring to Figs. 12 and 13. The

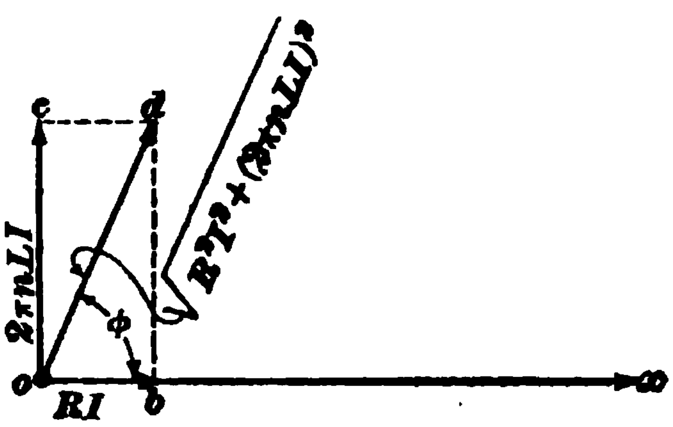


FIG. 12

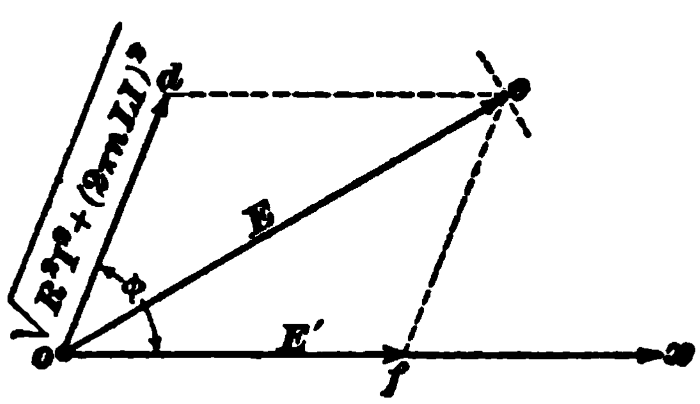


FIG. 13

alternator is supposed to be run at a constant speed with a constant strength of field; the total E. M. F. generated in the armature will therefore be constant, because the rate at which lines of force are cut does not change, no matter what current is taken from the machine. We will suppose that the alternator is working upon a non-inductive load, such as incandescent lamps, and we will represent the current in the external circuit by the line $o\,x$, Fig. 12. The E. M. F. necessary to overcome the armature resistance will be represented by $o\,b$ in phase with the current $o\,x$ and equal to RI; the E. M. F. necessary to overcome the armature reactance $2\pi n L I$ will be represented by $o\,c$ 90° ahead of the current; and the total E. M. F. necessary to overcome both resistance and reactance will be $o\,d = I\sqrt{R^2 + (2\pi n L)^2}$,

$\phi°$ ahead of the current in phase. The resultant sum of this E. M. F. $o\,d$ and the E. M. F. obtained at the terminals of the alternator must always be equal to the total E. M. F. generated E, which is of fixed value so long as the speed and field strength remain constant. Since the alternator is working on a non-inductive load, the terminal voltage E' must be in phase with the current and in the same direction as the current line $o\,x$, Fig. 13. The line $o\,d$, $\phi°$ ahead of $o\,x$ and equal to $o\,d$, Fig. 12, represents the amount and direction of the E. M. F. to overcome the armature impedance. Hence the total E. M. F. E must be the diagonal of a parallelogram that has its sides parallel to $o\,d$ and $o\,x$, and of which $o\,d$ is one side. The value of the terminal E. M. F. E' must therefore be $o\,f$, and it will be noticed that it is considerably less than the E. M. F. E.

By examining these two diagrams, it will be seen that if the inductance of the armature is large, compared with the resistance, the line $o\,d$ will be long and the angle ϕ nearly 90°. Consequently, the terminal E. M. F. E' obtained from a given E. M. F. E will be very small. If sufficient current is taken from a machine with large armature self-inductance, the terminal E. M. F. may fall to zero; that is, all the voltage generated is used up in overcoming the impedance of the armature and practically a wattless current is flowing. In this case, the effects of armature self-induction only have been considered. It will be shown later that the armature may exert a powerful demagnetizing action on the field in case the machine supplies an inductive load and the apparent armature reactance when the machine is running may be much greater than the reactance measured at standstill. The predetermination of the falling off in voltage with increase in load is therefore a complicated matter, as it depends not only on the armature inductance but also on the various effects of armature reaction. The apparent reactance that the armature possesses due to the combination of these effects is often called the **synchronous reactance** to distinguish it from the ordinary reactance which takes into account the self-induction only.

14. Alternators having high armature self-inductance may be short-circuited without much danger of burning them out. When a machine of this kind is short-circuited the current does not rise to a very large amount, as with direct-current machines, because the voltage generated is required to overcome the inductance, and is unable to set up a large current. As the load is increased, the E. M. F. falls off, at first slowly and then more rapidly, until, when a certain current is reached, the terminal E. M. F. has dropped to zero, and no further increase in current can take place. This is illustrated by Fig. 14, which shows a curve taken from an alternator with an armature of fairly high self-induction. The normal full-load current of this machine is 25 amperes, and it is seen that as the load is increased, the terminal voltage keeps falling off, until at short circuit the current is about 47 amperes and the terminal voltage zero. Such a machine would probably not be injured by a short circuit, because it would be able to carry a current of 47 amperes for some time without dangerously overheating the armature. At the same time such machines are not considered desirable, because good voltage regulation is of much more importance than incidental immunity from burn-outs.

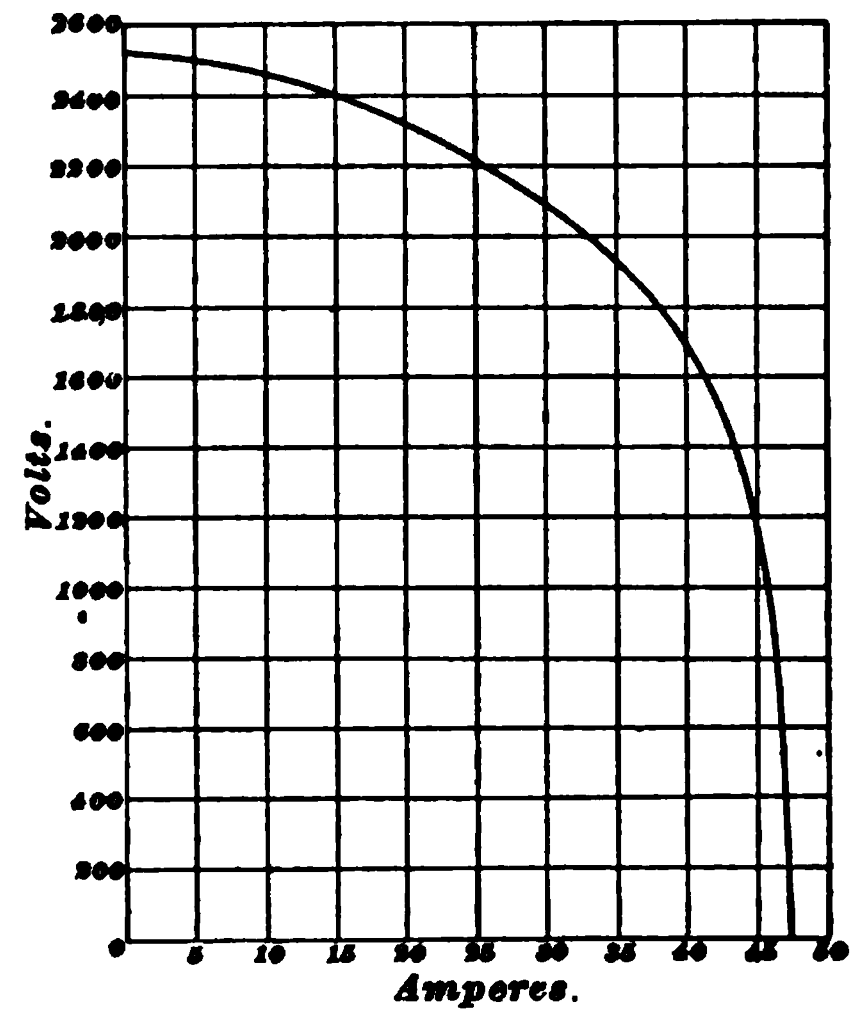


FIG. 14

15. The student will see from the above that the output of an alternator may be limited if the armature self-induction is too high, because the voltage may drop off before the machine is delivering the current that it is capable of

doing without overheating. The output of alternators is, of course, affected by the heating of the armature conductors, just as in the case of direct-current machines, and the output is in some cases limited by this effect rather than by the self-induction.

EXAMPLES FOR PRACTICE

1. If an alternator is to run at 1,200 R. P. M. and to give a frequency of 60 cycles per second, how many poles must it have? Ans. 6

2. How many poles should a 60-cycle alternator have if it is desired to couple it directly to a waterwheel running 225 R. P. M.? Ans. 32

3. A ten-pole alternator runs at the rate of 1,500 R. P. M. The armature is provided with ten coils of 40 turns each, connected in series, and the flux through each pole is 1,000,000 lines. What E. M. F. will the machine give at the collector rings when running on open circuit? Ans. 2,220 volts

---

FIELD EXCITATION OF ALTERNATORS

16. In most alternating-current systems, the voltage at the points where the current is distributed is kept constant, or nearly so. This means that the voltage at the terminals of the alternator must, as a rule, rise slightly as the load comes on, the amount of rise depending on the loss in the line. At any rate, the voltage at the terminals must not drop off, and, as it has been shown that, with constant field excitation, the voltage will fall off with the load, it becomes necessary to increase the strength of the field magnets as the current output of the machine increases. For accomplishing this there are two methods in use, which are analogous to those employed for the regulation of shunt- and compound-wound continuous-current machines.

17. The simplest method is that indicated by Fig. 15. W represents the armature winding, the terminals T, T' of which are connected to the collector rings R, R', connecting to the line by means of the brushes g, h. The field is excited by a set of coils on the pole pieces represented by C,

and current is supplied to these from a small continuous-current dynamo or exciter *E*. This is a small shunt-wound machine with an adjustable field rheostat *r* in its shunt field *f*. An adjustable rheostat *R* is placed also in the alternator field circuit. When the voltage drops, the fields may be

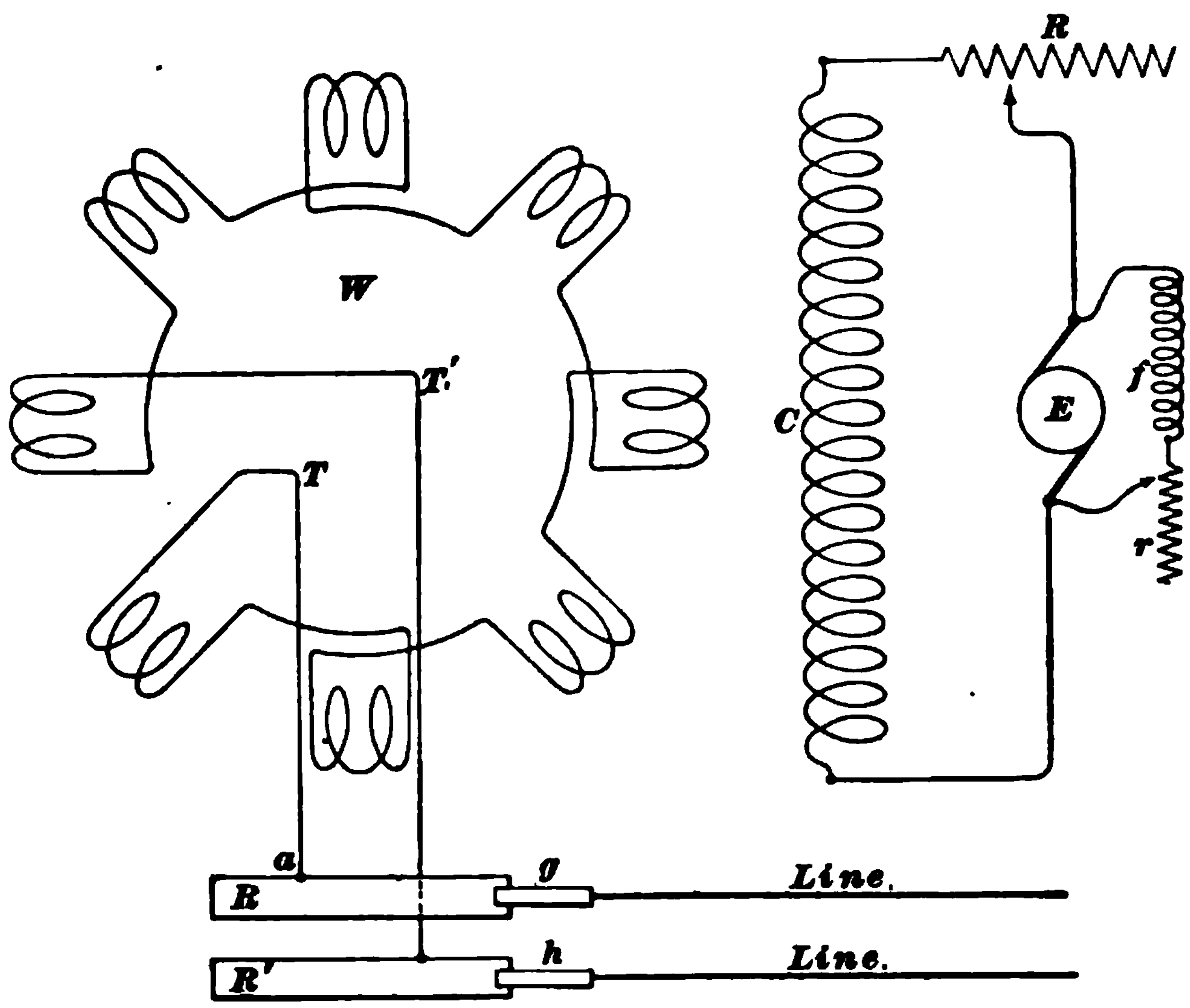


FIG. 15

strengthened by adjusting the resistances *R* and *r*. This method, which is used with plain separately excited alternators, serves to keep the voltage right, and may be used with advantage when a number of alternators are supplied from one exciter; but it is a hand method, and is therefore objectionable if the load varies much.

18. Another method, shown in Fig. 16, varies the excitation of the field in proportion to the current that the machine is supplying, and thus automatically keeps up the voltage. Each field coil in this case consists of two windings similar to those used on compound-wound continuous-current dynamos. One set of windings is separately excited by means of the exciter *E*, and is provided with a rheostat *R*,

as in the previous case. The field of the exciter is also provided with a rheostat r. The greater part of the current furnished by the alternator flows through the series-winding, represented by the heavy coil S; and since this causes the magnetism to increase, the machine maintains its voltage.

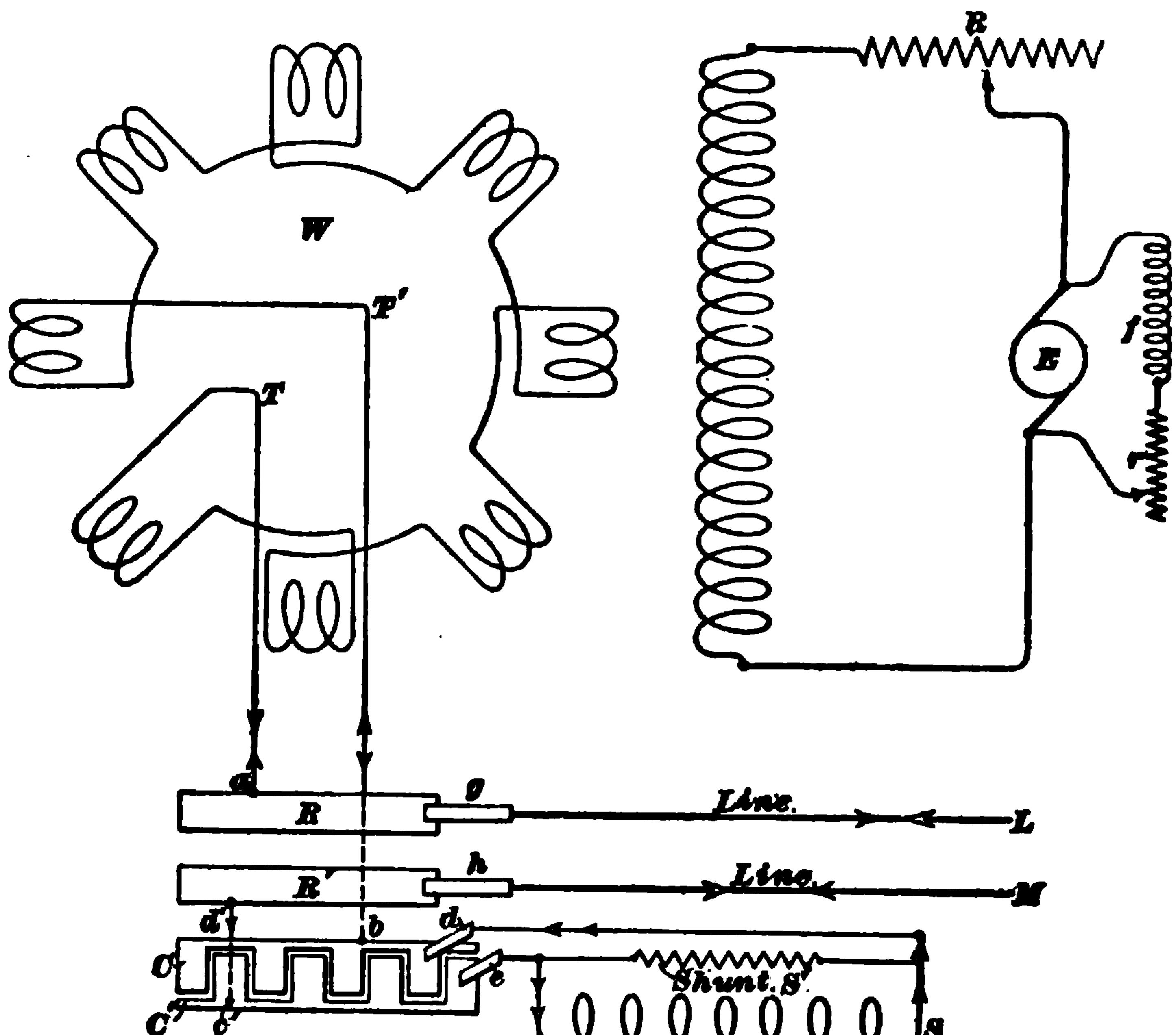


FIG. 16

The separately excited coils set up the magnetism necessary for the generation of the voltage at no load, and the series-coils furnish the additional magnetism necessary to supply the voltage to overcome the armature impedance.

19. The current flowing in these series-coils must not be alternating, because if it were it would tend to strengthen the poles one instant and weaken them the next, and on this account the current must be rectified before being sent around the field. This is accomplished by means of the

commutator, or **rectifier,** CC', which is mounted on the shaft alongside the collector rings. It consists of two castings C, C' (shown developed in the figure), which are fitted together and form a commutator of as many sections as there are poles in the machine. The alternate sections are connected by the conductors c, c', as shown in Fig. 17, the light sections belonging to one casting C' and the dark to the other C. Two brushes d and e, which press on the commutator, are so arranged that one is always in contact with C, while the other touches C'.

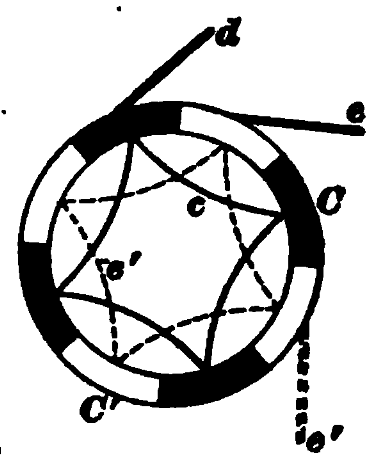


FIG. 17

The connections are as shown in the diagram. One terminal T of the armature winding connects directly to the ring R and thence to the line. The other terminal T' connects to one side of the rectifier C, and the other side C' is connected to the remaining ring R'. By following the direction of the current, it will be seen that while the rectifier causes the current to flow in the same direction in the series-coils S, it still remains alternating in the line circuit. Take the instant when the coils occupy such a position that the current is flowing from the terminal T, and mark the direction of flow in the different parts of the circuit by the closed arrowheads. The current will flow out on the line L, back on M to C', through S, flowing from left to right, back to C, and thence back to the armature. When the armature has turned through a distance equal to that between two poles, the current will be flowing in the opposite direction, as indicated by the open arrowheads; that is, it will be flowing out from T' to C, from C it will go to the brush e instead of d, because it must be remembered that the rectifier has turned through the same angle as the armature, and hence d has slid from C on to C'. From e the current flows through S in the same direction as before, back to C', out on the line M, and back on L to T. The action of the rectifier is, briefly, to keep changing the connections of d and e as the current changes, thus keeping the current in S in the same direction while it remains alternating in the

line. Usually the brushes *d*, *c* are placed on the commutator as shown by *d* and *e'*, Fig. 17, in order to have them farther apart, their action, however, being the same. A shunt resistance *S'*, Fig. 16, is usually placed across the coils *S*, in order to adjust the compounding of the machine to the circuit on which it is to work, since by varying *S'*, the percentage of the total current passing around the field can be changed. This method of excitation has been largely used by the General Electric Company for their compound-wound alternators.

20. Fig. 18 shows a method of compounding used on Westinghouse alternators. It is somewhat similar to the

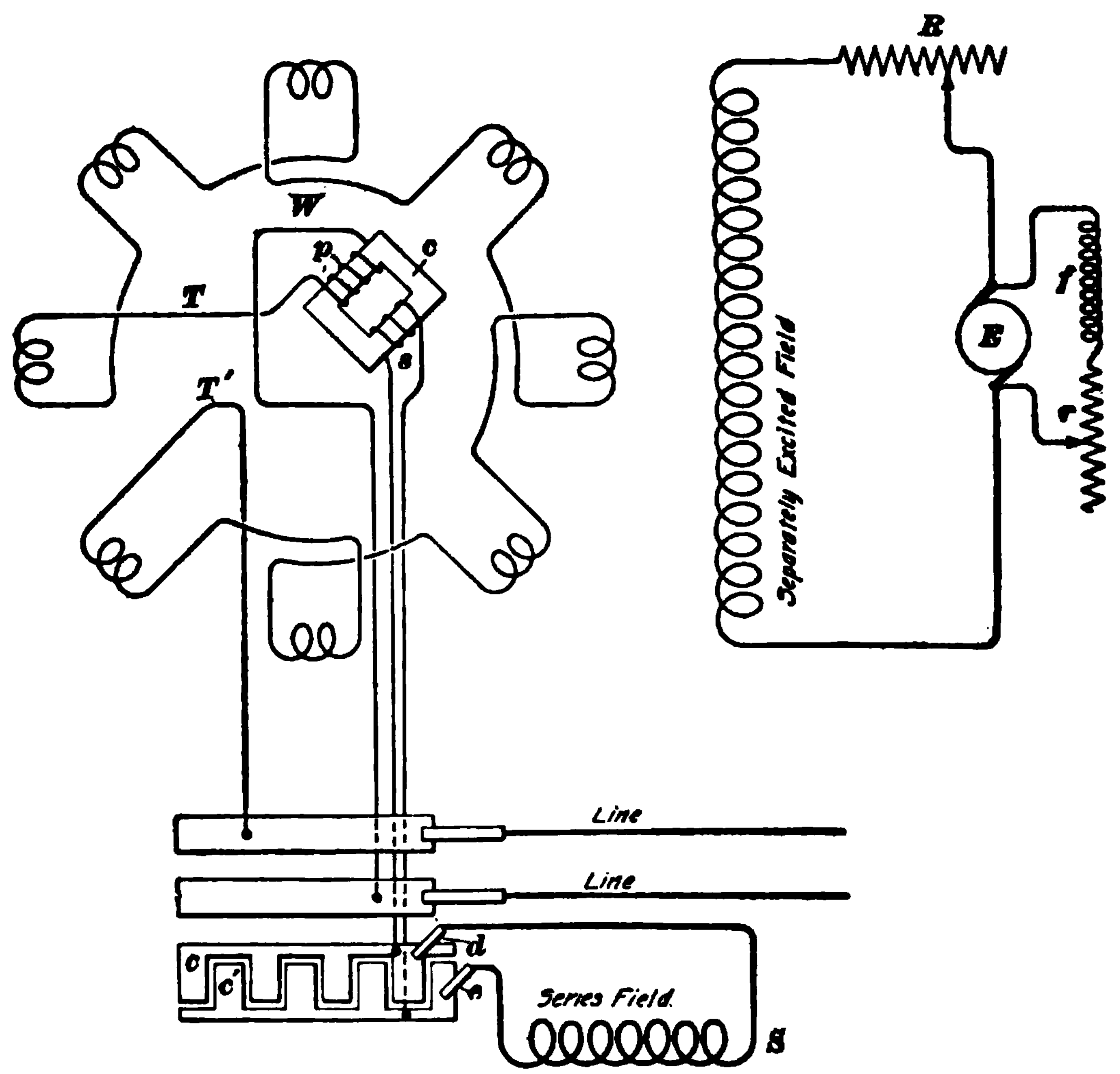


FIG. 18

method last described so far as the action of the rectifier is concerned, but differs in the means used to supply the

series-fields with current. The main current from the armature is not led through the series-coils, as in the last method, but is carried through the primary coil *p* of a small transformer that is mounted on the armature spider and revolves with it. In some machines, the laminated core *c* on which coils *p* and *s* are wound, is a portion of the armature spider, the armature disks being punched out so as to form spokes on which the coils are placed. The secondary coil *S* is connected to the parts *c*, *c'* of the rectifier. Coils *p* and *s* are thoroughly insulated, so that it is easily seen that the series-coils have no electrical connection with the armature winding. The main current flowing through *p* sets up an alternating magnetism in the iron core *c*, and this in turn induces an E. M. F. in coil *s*, as explained later in connection with transformers. As the armature current in *p* increases, the current in *s* and the series-coils also increases, and thus regulates the field excitation so as to keep up the pressure. The action of the rectifier is the same as before, its function being to make the current supplied from *s* flow through the series-field always in the same direction. One advantage of this method of compounding is that the high-tension current of the armature is not in any way connected to the field windings, thus rendering their insulation less difficult and reducing the liability of shocks to the dynamo tender.

REVOLVING-FIELD AND INDUCTOR ALTERNATORS

21. It has been mentioned that it makes no difference in the case of an alternator whether the field or armature is the revolving part. It is hardly practicable to make a direct-current dynamo with a revolving field and stationary armature, because it is necessary that the brushes should always press on the commutator at certain neutral points that bear a fixed relation to the field, and the brushes would, therefore, have to revolve with it. This, of course, would be objectionable, because it is often necessary to get at the brushes

while the machine is running. In an alternator, the brushes pressing on the collector rings do not have to bear any fixed relation to the field, consequently there is no objection to the use of a fixed armature, the current from which can be carried off by leads connected to the winding. Two collector rings are necessary for carrying the exciting current into the revolving field, so that the use of the stationary armature does not do away with moving contacts, but the collector rings for the exciting current are subjected to a low pressure compared with that generated in the armature, and hence are easy to insulate and handle. The revolving-field type has an advantage in that the armature, being stationary, is easy to insulate for high voltages. This construction also admits of the ready use of armatures of large diameter, thus rendering such machines particularly adapted to slow speeds.

22. Alternators of the revolving-field type have come into extensive use, and some have been built generating

A

Fig. 19

pressures as high as 10,000 or 12,000 volts. The arrangement of the parts of this type of machine is usually similar

to that shown in Fig. 19. This shows a portion only of the stationary armature, which is external to the revolving field. The armature core is built up of a large number of sectional stampings *C* provided with slots on their inner periphery, and the whole core structure is clamped in a cast-iron yoke *A* by means of the flange *B*. The armature coils *D* are held in the slots by means of wooden wedges in much the same way as in the revolving-armature machines. The field structure is made up of a cast-steel rim *G* carried by the arms *H*, which terminate in a hub keyed to the shaft. Laminated pole pieces *E* are bolted to *G* by means of bolts *F*, and the field spools *K* are held on by means of flanges *O*. These coils are connected together, and the leads *L*, *M* are connected to two collector rings on the shaft by means of which the exciting current is supplied.

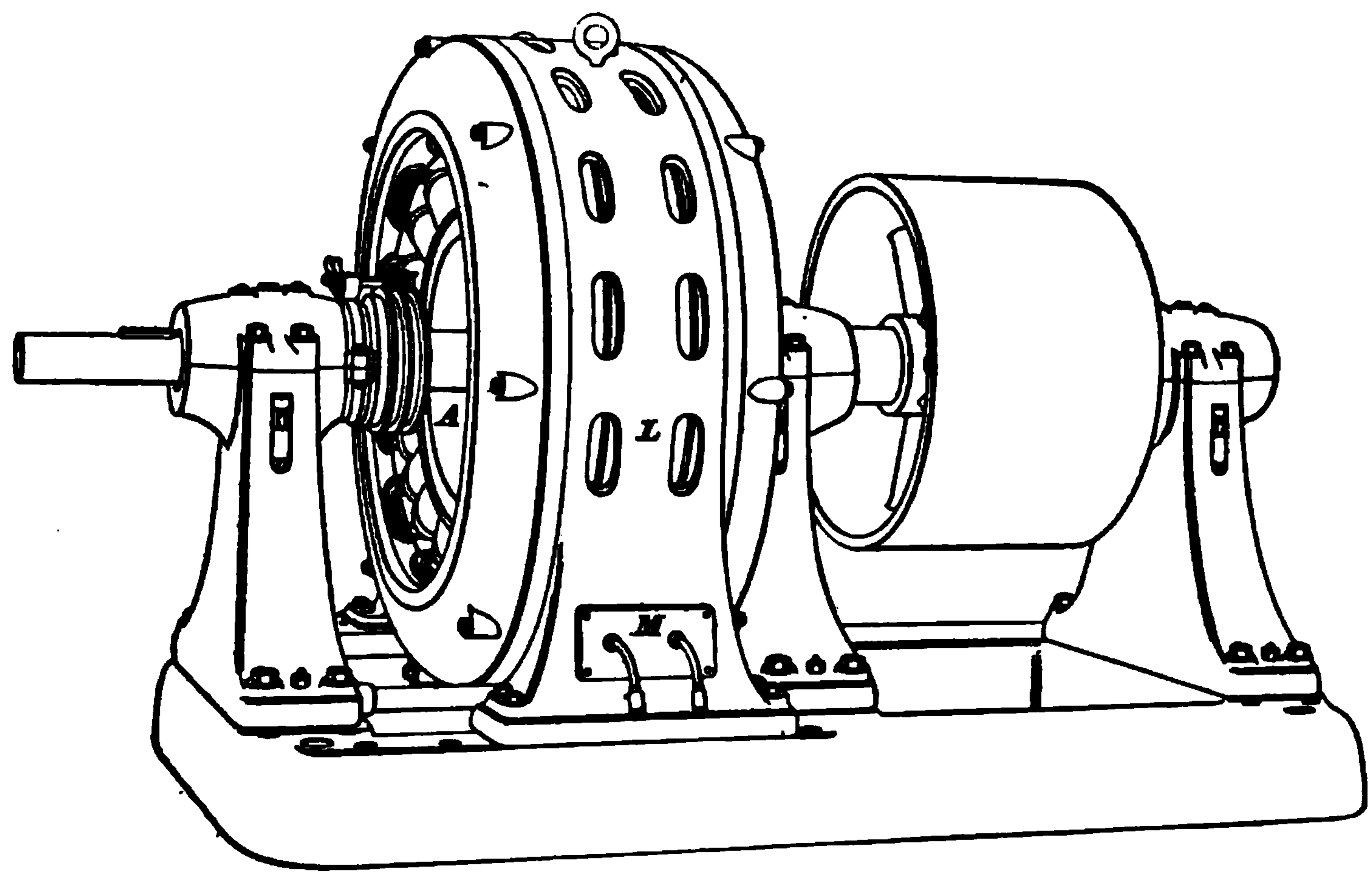


FIG. 20

Fig. 20 shows a revolving-field alternator of the belt-driven type. This is a single-phase machine. The terminals of the stationary armature are shown at *M*, while *A* is the revolving field. Fig. 21 shows the general construction. *G* is the laminated armature core supported by the cast-iron framework *L*; *f*, *f* are the armature coils; *B* is a

steel ring into which the pole pieces are dovetailed at *e* and held by means of keys. The exciting coils *d* are made up of copper strip wound on edge.

FIG. 21

23. In the inductor type of alternator, the collector rings for supplying current to the field may be done away with, and a machine obtained that has no moving contacts whatever. In this class of machine, a mass of iron, or **inductor,** with projecting poles is revolved past the stationary armature coils. The magnetism is set up by a fixed coil encircling the inductor; and as the iron part revolves, the magnetism sweeps over the face of the coils, thus causing an E. M. F. to be set up.

Fig. 22 shows the principle of the Westinghouse inductor alternator. In this machine the circular iron frame E supports the laminations F, which constitute the armature core. These are provided with slots in which the coils G are placed. Inside the armature is the revolving inductor A, provided with the projections C built up of wrought-iron or steel laminations. The circular exciting coil D is stationary

and encircles the inductor A, thus setting up a magnetic flux around the path indicated by the dotted line. The projecting poles C are all, therefore, of the same polarity, and as they revolve, the magnetic flux sweeps over the coils. Although this arrangement does away with collector rings, the machines are not so easily constructed as other types, especially in the large sizes. The coil D becomes large and

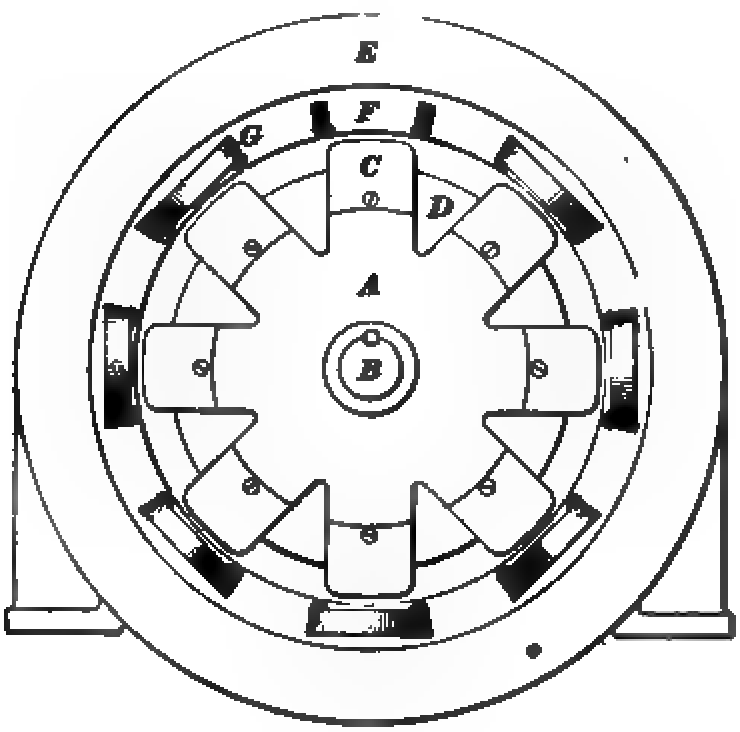


FIG. 22

difficult to support in place, and would be hard to repair in case of breakdown. The collector rings supplying a low-tension current to revolving-field coils should give little or no trouble; so, taking all things into consideration, it is questionable whether the inductor machine possesses much advantage over those with the revolving field. The Warren machine operates on the same principle as the Westinghouse machine shown in Fig. 19.

24. The most prominent example of the inductor alternator as used in America is the Stanley machine. This is made in several different sizes, one of the larger machines being represented by Fig. 23. In this view, the halves A, A of the stationary armature are shown drawn back, so as to

allow access to the coils. When the machine is in operation, these halves are bolted together by means of bolts

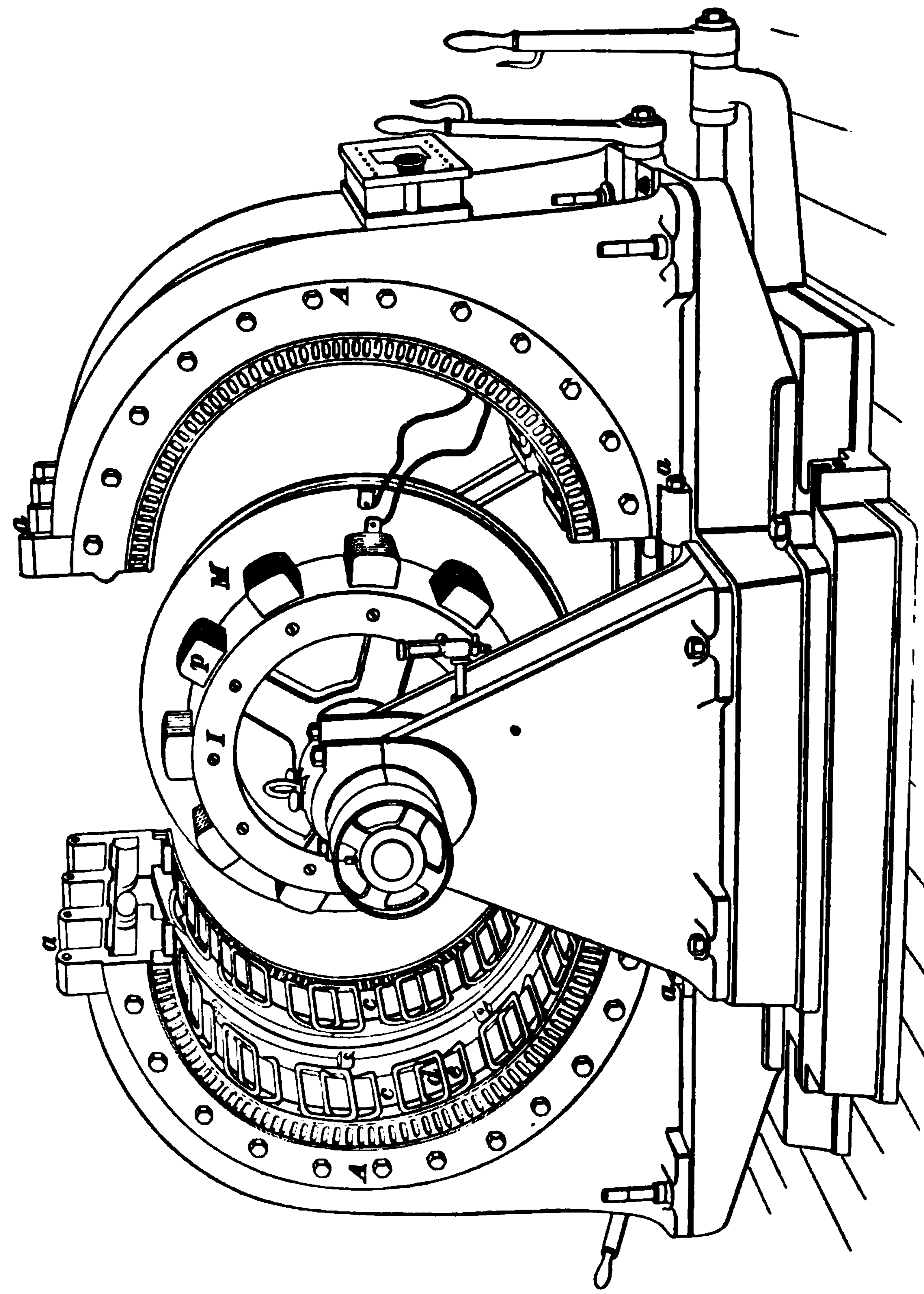


Fig. 23

passing through the lugs *a*, *a*. The machine is double, there being two laminated cores *c*, *c*, in the slots of which the coils *d*, *e* are mounted (see also Fig. 24). It will be

noticed that the coils marked *d* are placed midway between those marked *e*, one set of coils overlapping the other. The result of this arrangement is that when half the conductors of one set of coils are directly under the poles, the conductors of the other set are out from under the poles; hence, when the current in one set is at its maximum value, the current in the other set is at its minimum value, thus making this particular machine deliver two currents that differ in phase by 90°. The machines can also be built to supply single-phase or three-phase currents, if desired. The revolving inductor is shown at *I*, Fig. 23, surrounded by the magnetizing coil *M*. All the polar projections *p* on one side of the coil are of the same polarity, and there is a similar set of opposite polarity on the other side of the coil. The construction will be understood by referring to Fig. 24,

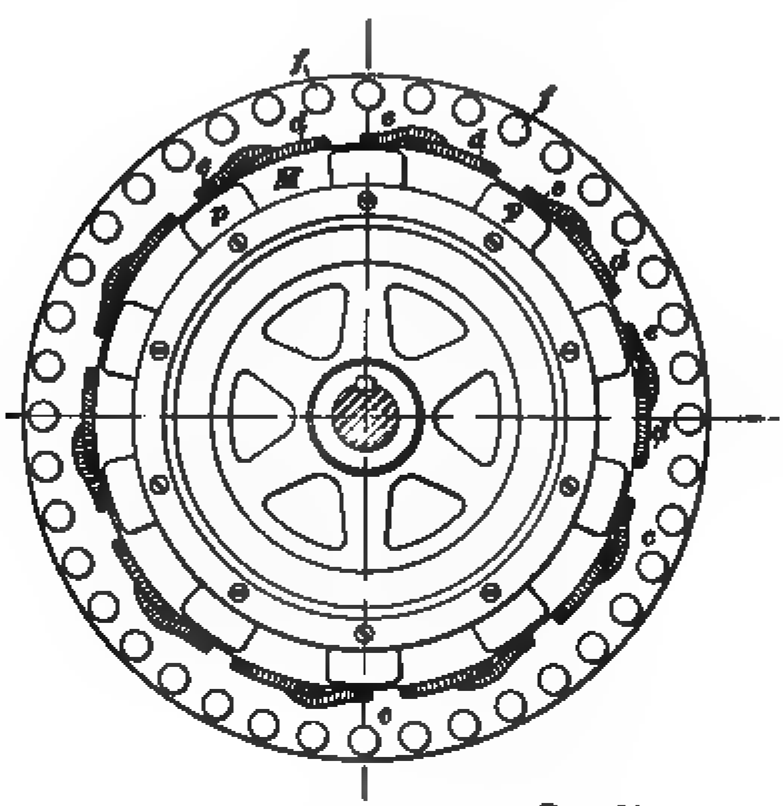


FIG. 24

which shows an end view and section of a large Stanley machine, the different parts being lettered to correspond with those shown in Fig. 23. The heavy iron bars *f*, *f* serve to hold the core together and also to carry the magnetism. The path of the magnetic flux is indicated by the dotted line

1–2–3–4, and when the inductor revolves, the lines of force sweep across the stationary coils and thus set up the required E. M. F. Inductor machines have the advantage of having no moving wire about them, but machines of the revolving-field type, such as shown in Fig. 20, have the advantage of using small field coils that are easily repaired or replaced in case of accident. The revolving-field type is also cheaper to construct, especially in machines for low speed and frequency, and gives better voltage regulation.

POLYPHASE ALTERNATORS

25. The alternators discussed so far have all been considered as machines that furnish one current only, and are, consequently, known as **single-phase alternators.** Mention has been made of machines which, being provided with two or more distinct sets of windings on their armatures, are capable of furnishing two or more currents to the lines. Such are known as **polyphase,** or **multiphase,** alternators. The two kinds in common use are two-phase, or quarter-phase, alternators and three-phase alternators.

Two-phase, or quarter-phase, machines deliver two currents that differ in phase by 90°.

Three-phase machines deliver three currents that differ in phase by 120°.

TWO-PHASE ALTERNATORS

26. Since a two-phase machine delivers two currents differing in phase by 90°, it follows that the two windings on its armature must be so arranged that when one set is delivering its maximum E. M. F., the E. M. F. of the other is passing through zero. It has been shown that while the coils move from a point opposite the center of one pole piece to a point opposite the next of the same polarity the E. M. F. passes through one complete cycle; hence, if the E. M. F.'s generated by the two sets of coils are to be displaced 90°, or

¼ cycle, with reference to each other, it follows that one set of coils must be placed one-half the pitch behind the other. This brings one set of conductors under the poles while the other set is midway between them.

27. It has been shown that for the most effective generation of E. M. F. the wire on an alternator armature does not cover all the surface, and an armature such as shown in Fig. 5 could have another set of coils added, so as to produce an E. M. F. at 90° with that generated by the coils already shown on the drum. Such a winding is shown in Fig. 25, except that in this case there are only

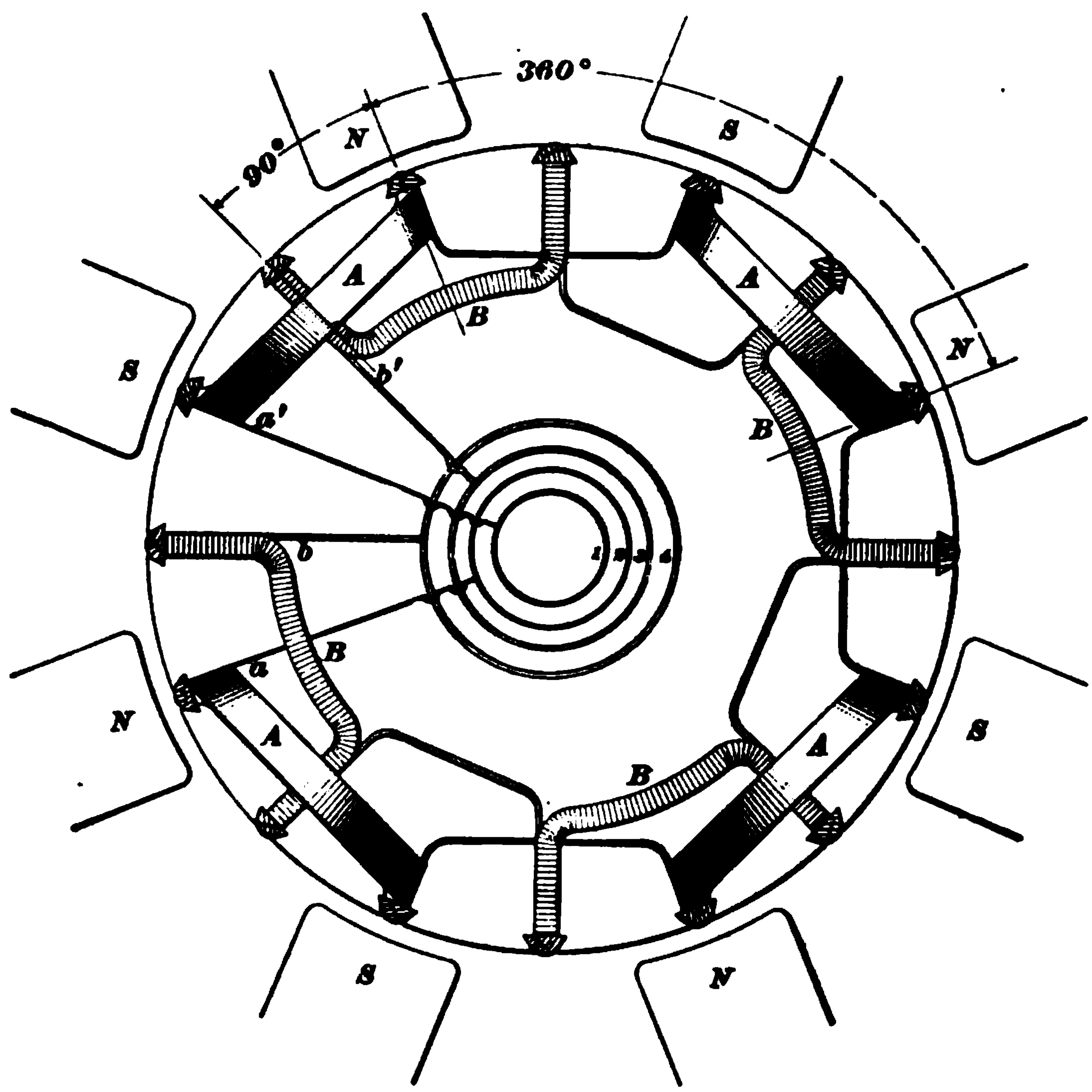


FIG. 25

four coils in each phase instead of eight. This gives a common type of two-phase winding, and is used instead of the eight-coil arrangement, in order not to make the

drawing too confused. Fig. 25, therefore, represents a two-phase winding having one group of conductors or one-half a coil per pole per phase. One phase is made up of the four coils *A*, which are connected in series, and the terminals *a*, *a'* brought out to the collector rings *1*, *2*. The four coils *B*, which make up the second phase, are also connected in series, and the terminals *b*, *b'* attached to the light collector rings *3*, *4*. The angular distance by which the center of set *B* is displaced from set *A* is equivalent to 90°, or ¼ cycle, as indicated in the figure, the angular distance from *N* to *N* being equivalent to 360°, or one complete cycle.

28. Fig. 25 shows a common method of connecting up two-phase windings; namely, the method employing two distinct circuits and four collector rings. This may be shown diagrammatically, as in Fig. 26. The windings are here represented by coils *1* and *2* connected to the collector rings *a*, *a'* and *b*, *b'*. These windings have no electrical con-

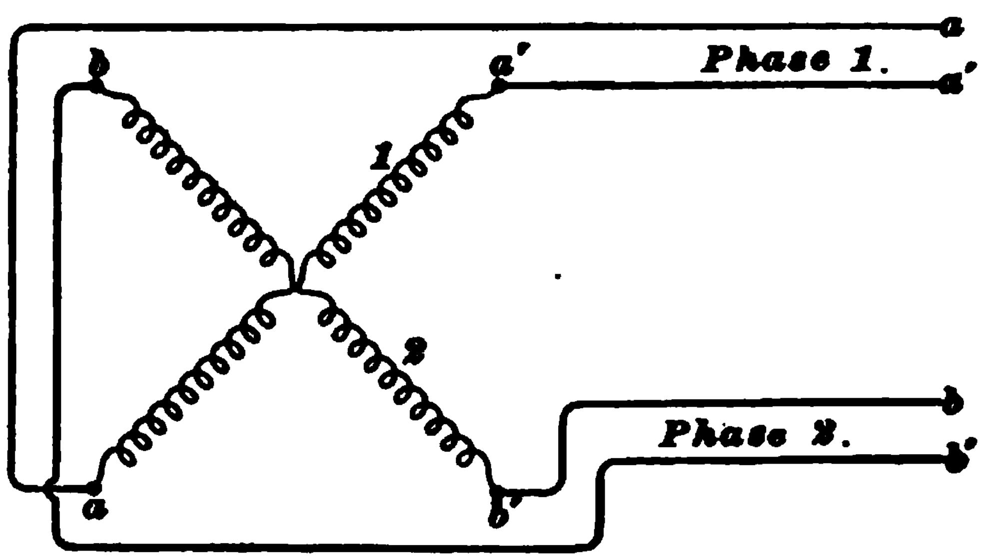


FIG. 26

nection with each other and connect to two distinct circuits. In Fig. 26 the two armature windings are independent, but they might be connected at their middle points (where they cross each other in the figure) and thus form an interlinked system. If this were done, the pressure between lines *a' b* or *a b'* would be $\frac{E}{\sqrt{2}}$, where *E* is the pressure between *a b* or *a' b'*, i. e., the voltage generated in each phase. Later

on another type of interlinked quarter-phase winding is described in connection with alternators having closed circuit armature windings. The terms two phase and quarter phase are commonly applied to any machine that delivers two currents differing in phase by one-quarter of a cycle. As we have just seen, such a machine may have its windings interlinked or independent, and some writers refer to the interlinked type as quarter phase and to the independent type as two phase, though such distinction is by no means general.

29. Sometimes, instead of using two distinct circuits with four collector rings, a common return wire is employed, as indicated in Fig. 27. Here one end of each of the phases

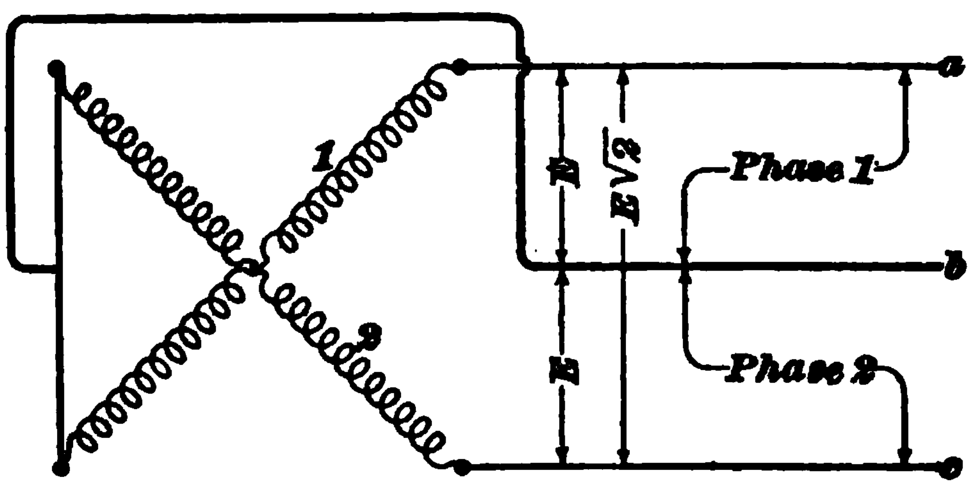


FIG. 27

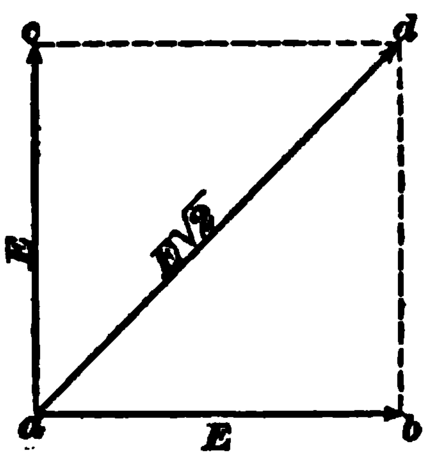


FIG. 28

is joined to a common return wire, and only three collector rings are necessary. If E represent the E. M. F. generated per phase, the voltage between $a\ b$ and $b\ c$ will be E, while that between $a\ c$ will be $E\sqrt{2}$. This will be understood by referring to Fig. 28, the E. M. F. between a and c being the resultant of the two equal E. M. F.'s E at right angles to each other.

30. Fig. 29 is the winding diagram showing the method of connecting up the coils of the armature, Fig. 25. This winding differs from that shown in Fig. 6, in that the connections of every alternate coil do not have to be reversed. By marking the direction of the E. M. F.'s by arrowheads,

as before, it is readily seen that the terminal *1'* must be connected to *2*, *2'* to *3*, and so on. The difference in the method of connecting the two windings is caused by there being only four coils per phase in Fig. 29, whereas there are eight

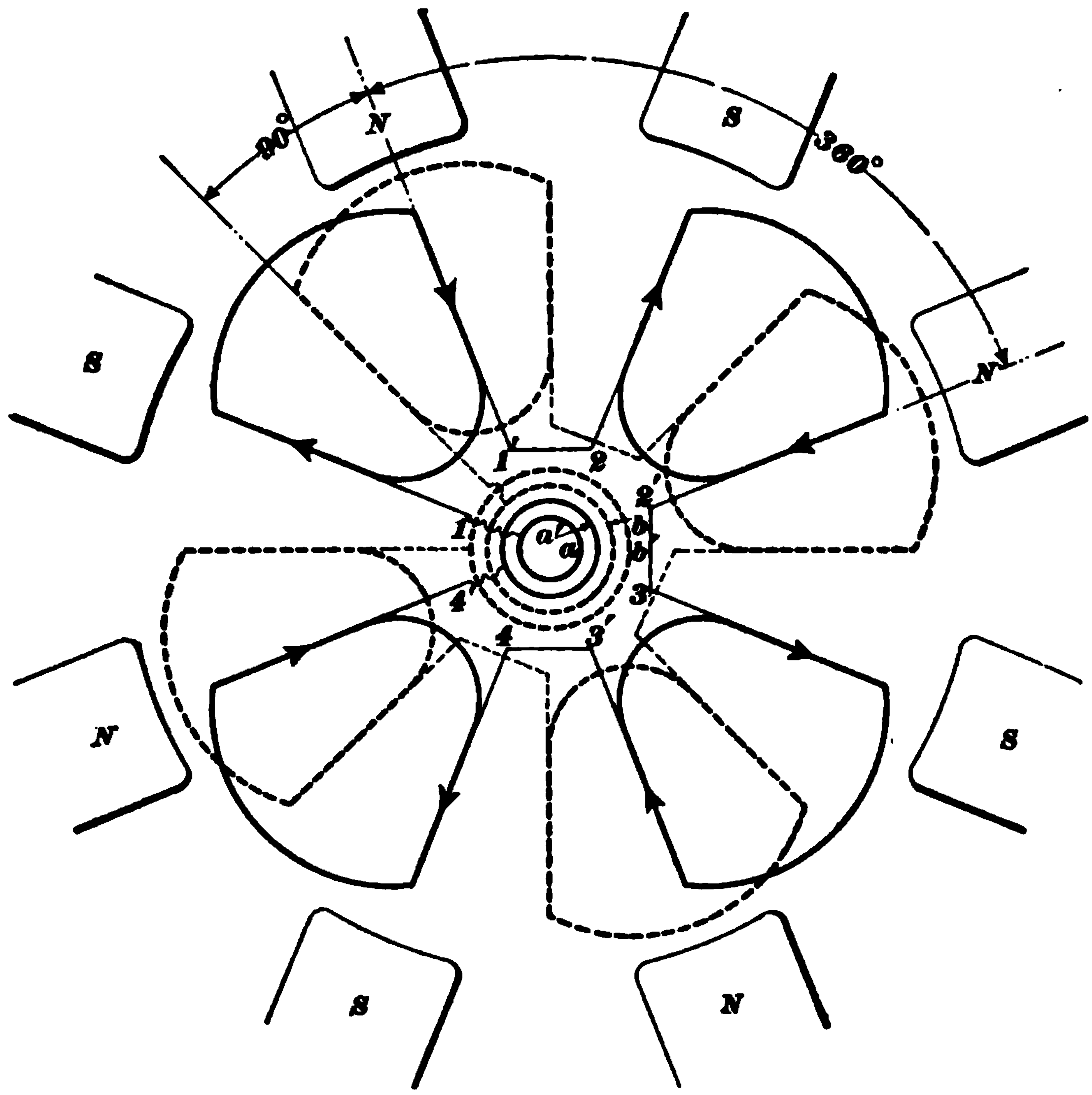


FIG. 29

in Fig. 6. The coils of the second phase are shown dotted, and the connections between them are made in exactly the same way as those of the first phase.

31. For delivering heavy currents at low voltages, armatures are sometimes wound with copper bars. In such cases there is usually only one turn, or two bars, per coil, and such a bar winding is shown in Fig. 30. This is the equivalent of the coil arrangement shown in Fig. 29, the

connections between the bars being such that the current flows in accordance with the arrows. Windings of this kind are used on machines for furnishing heavy currents necessary for electric smelting or any other purposes that call for a large current.

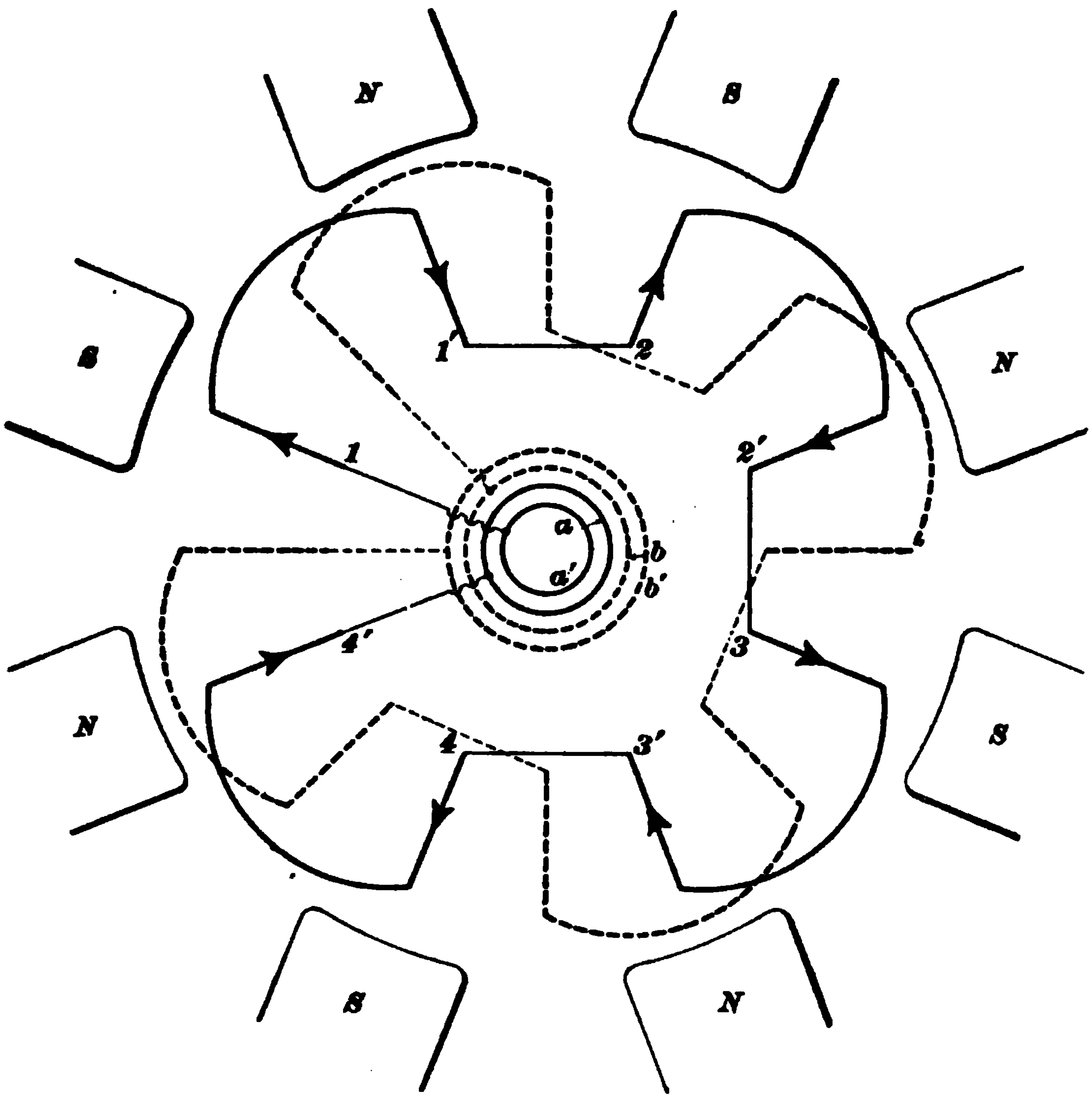


FIG. 30

32. The two-phase windings shown in Figs. 25, 29, and 30 are of the simpler kind known as **concentrated** or **uni-coil windings.** The conductors on a two-phase armature may be distributed in the same way as those of single-phase machines, there being two, three, or more coils per pole per phase. Both styles are in common use, and will be treated in greater detail in connection with alternator design.

33. Polyphase machines are used principally for operating power systems, though lamps are often run from them as well. For example, in Fig. 26 lamps could be connected across either of the phases, and in case a motor were to be connected, both phases would be used. The load on the different phases should be kept as nearly balanced as possible. It is usual to rate the output of alternators by the power they are capable of supplying a non-inductive circuit; that is, by the product of the volts and amperes that they can furnish without overheating. The output of a two-phase machine is the sum of the outputs of the separate phases. For example, if it were said that a certain two-phase alternator had an output of 150 kilowatts, at a voltage of 2,000, it would mean that the volts generated by each phase was 2,000, and hence the total full-load current with the machine working on a non-inductive resistance would be 75 amperes, or 37½ amperes per phase. Each line and the wire on the armature would therefore have to be capable of carrying 37½ amperes. If the machine were working on an inductive load, the product of the volts and amperes would not give the output in watts, on account of the lagging of the current. The current in this case would have to be greater for a given output, and as the current output is limited by the size of the armature wire, it follows that an alternator will not deliver its full load rating to an inductive circuit. If the above alternator were provided with only three lines and three collector rings, as in Fig. 27, the current in the common return wire would be $37\frac{1}{2} \times \sqrt{2} = 53$ amperes, nearly. The two outside wires would in this case be proportioned for 37½ amperes and the middle wire for 53 amperes.

EXAMPLE.—A two-phase alternator is to have an output of 200 kilowatts at a pressure of 2,000 volts, and is to be operated on a three-wire circuit. What will be the full-load current in each of the three wires, and what current must the wire on the armature be capable of carrying?

SOLUTION.—Output per phase = 100 kilowatts. Hence, full-load current per phase = $\frac{100000}{2000} = 50$ amperes. The current in the two outside wires is therefore 50 amperes, and the wire in each set of armature coils must be capable of carrying 50 amperes also. The current in the common return wire is $50 \times \sqrt{2} = 70.7$ amperes. Ans.

The field magnet of polyphase machines is identical with that used for single-phase machines; in fact, the only distinguishing feature of the former is the armature winding, the other parts of the machine being almost exactly the same, with perhaps a few minor changes, such as an increase in the number of collector rings, etc.

THREE-PHASE ALTERNATORS

34. The requirement of a three-phase armature winding is that it shall furnish three E. M. F.'s differing in phase by 120°, or one-third of a complete cycle. This can be done by furnishing the armature with three sets of windings displaced 120° from each other. This means that phase No. 2 must be one-third the angular distance from one north pole to the next north pole behind phase No. 1, and also that phase No. 3 shall be displaced a similar angular distance behind No. 2. Such an armature will deliver three E. M. F.'s differing in phase, as indicated in Fig. 31. The three E. M. F.'s are equal, and are represented by E_1, E_2, and E_3, each being 120° behind the other.

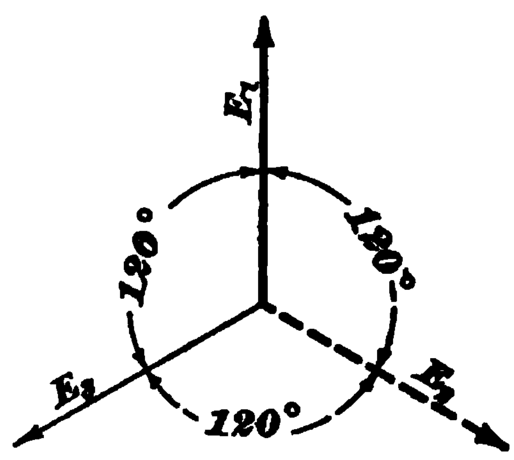


FIG. 31

35. Fig. 32 shows a three-phase winding having one-half coil or one group of conductors per pole per phase. This is the three-phase winding corresponding to the two-phase arrangement shown in Fig. 25. The winding consists of three distinct sets of coils *A*, *B*, and *C*. The angular distance from the center of coil *B* to *A* is equivalent to 120°, or is one-third of the distance from *N* to *N*; also the coil *C* is displaced the same distance behind *B*. Each of these three sets is connected in series, leaving the three pairs of terminals *a*, *a'*; *b*, *b'*; *c*, *c'*. The coils are shown diagrammatically in Fig. 33, phase *1* being represented by the

heavy lines, phase *2* by the dotted, and phase *3* by the light full lines.

Fig. 34 shows the same winding as Fig. 32 with a somewhat different mechanical arrangement of the coils. Coils belonging to the same phase are shaded and lettered alike

FIG. [illegible]

so that they can be readily distinguished. This arrangement of coils would be better in practice than that shown in Fig. 32, and is the one generally used for this type of winding. By allowing the straight coils to project at each end beyond the armature core, the crossings of the coils are much more easily arranged than in Fig. 32, thus making the winding easier to apply and insulate.

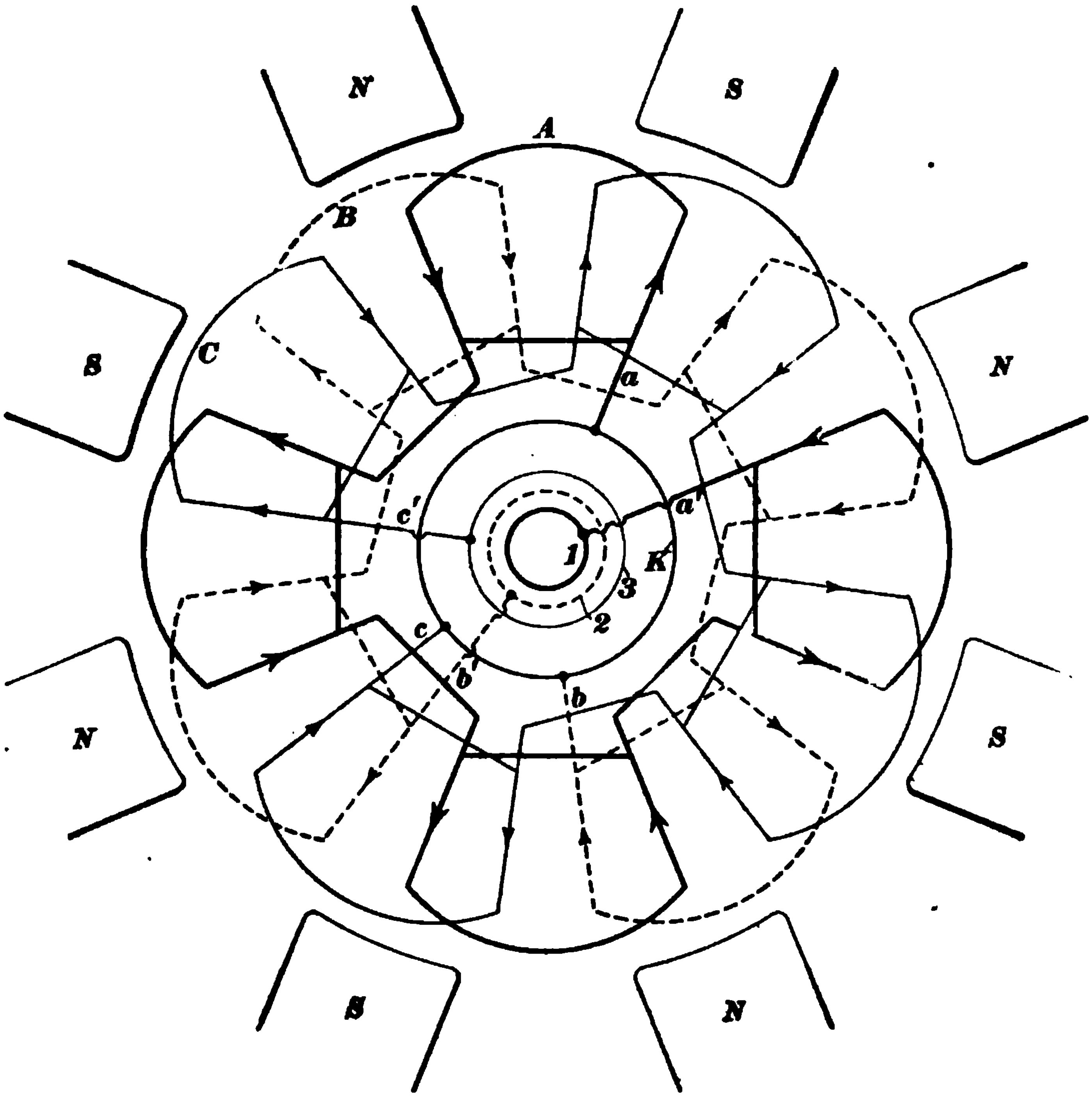


FIG. 33

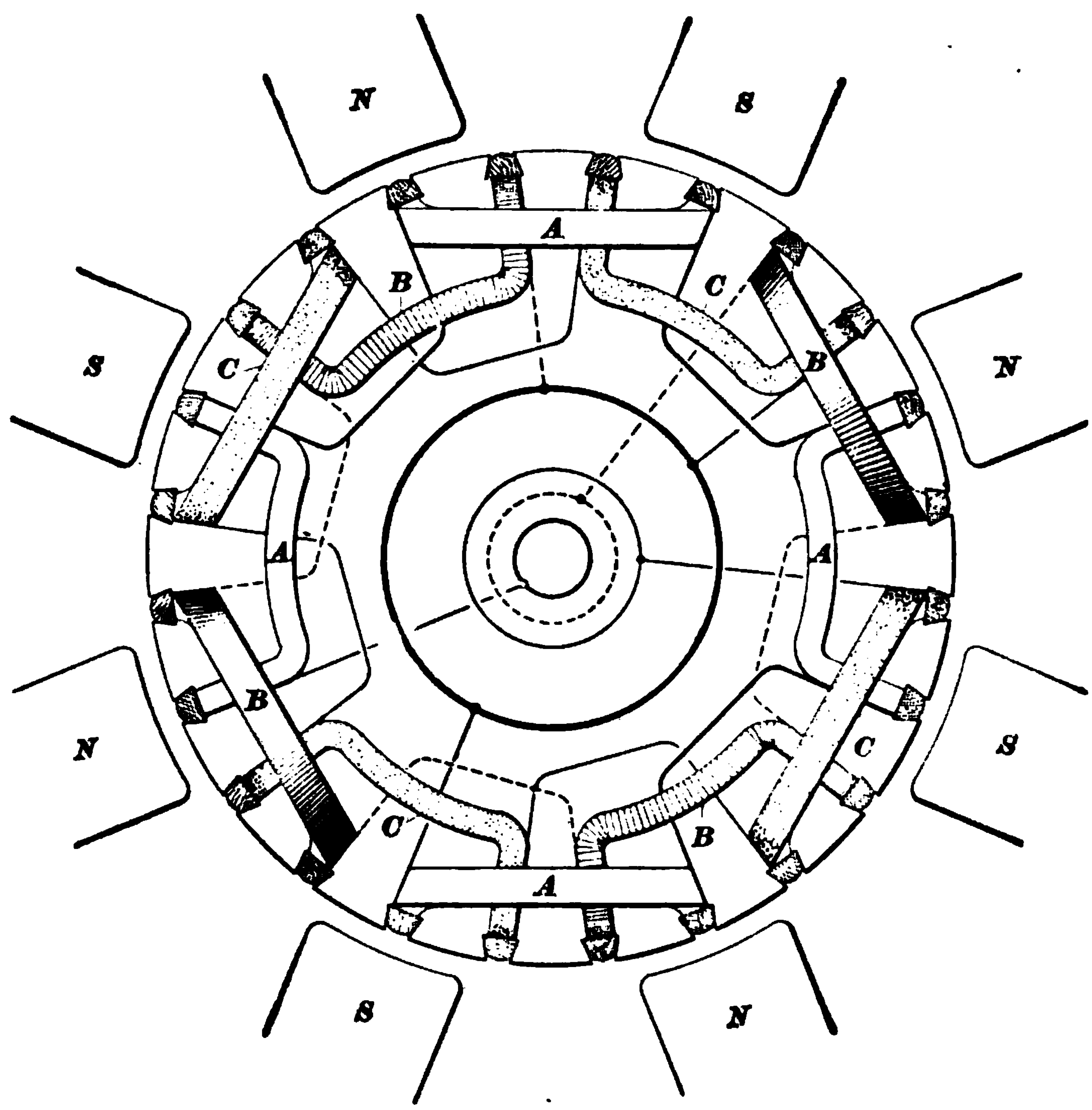


FIG. 34

STAR AND DELTA CONNECTIONS

36. There are two or three different ways in which the three pairs of terminals *a–a'*, *b–b'*, *c–c'*, Fig. 32, may be connected to the collector rings. In the first place, each terminal might be run to a ring, as was done in the case of the

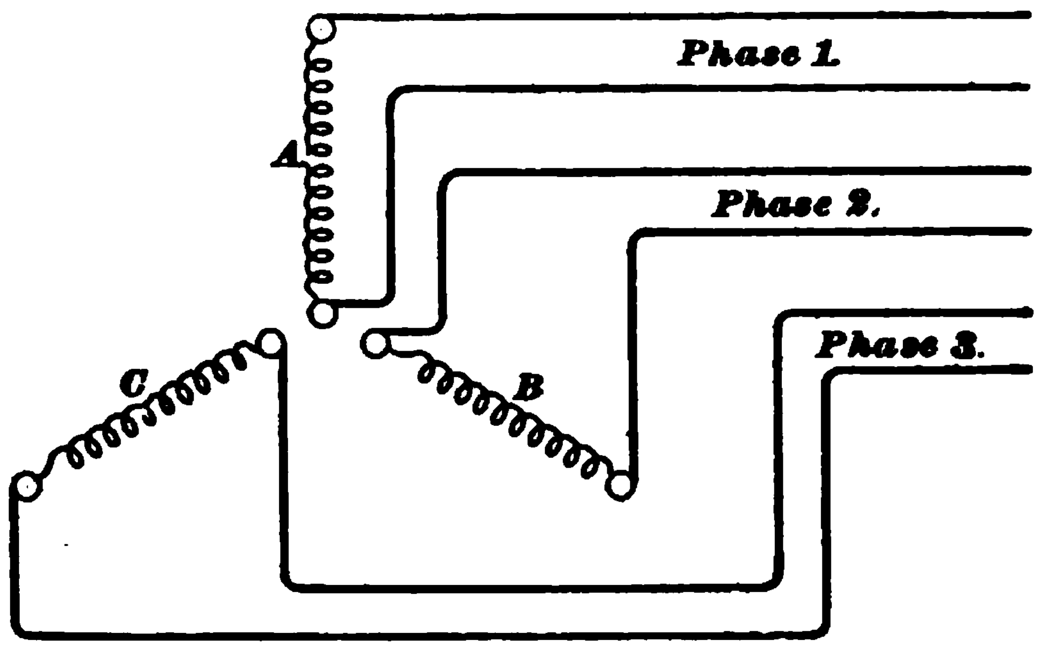


FIG. 35

two-phase armature. This would give three pairs of lines and six collector rings, as shown in Fig. 35. This is seldom, if ever, done in practice, as it complicates matters,

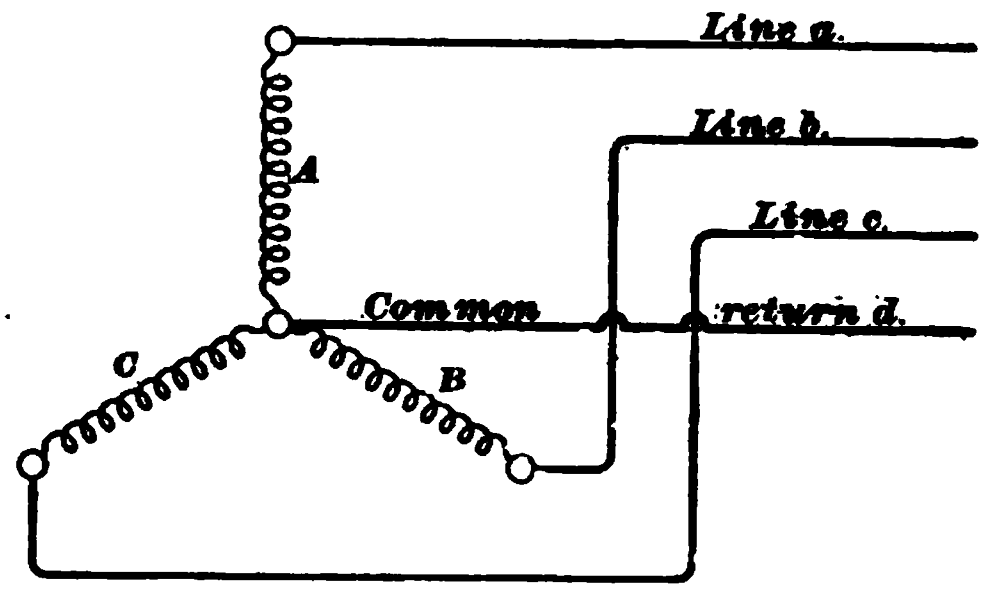


FIG. 36

and, moreover, it is not necessary. Again, one end of each of the three phases might be connected together, as shown in Fig. 36, and a common return wire *d* run from the common connection, forming an arrangement similar to the

two-phase three-wire system, Fig. 27. This would necessitate four collector rings, and is used occasionally on alternators that are to be used considerably for lighting work. The return wire from the common junction is also sometimes employed on three-phase distributing systems. It has been pointed out that the resultant sum of three *equal* currents displaced 120° is at all instants equal to zero. Consequently, if the resultant current is zero, there is no need of a return wire *d*, so it may be omitted. However, in some cases, where power is distributed from transformers or three-wire systems, the different branches are apt to become unbalanced. Under such circumstances the common return *d* is sometimes used.

37. Omitting the common wire *d* of Fig. 36 gives the arrangement shown in Fig. 37, in which one end of each of

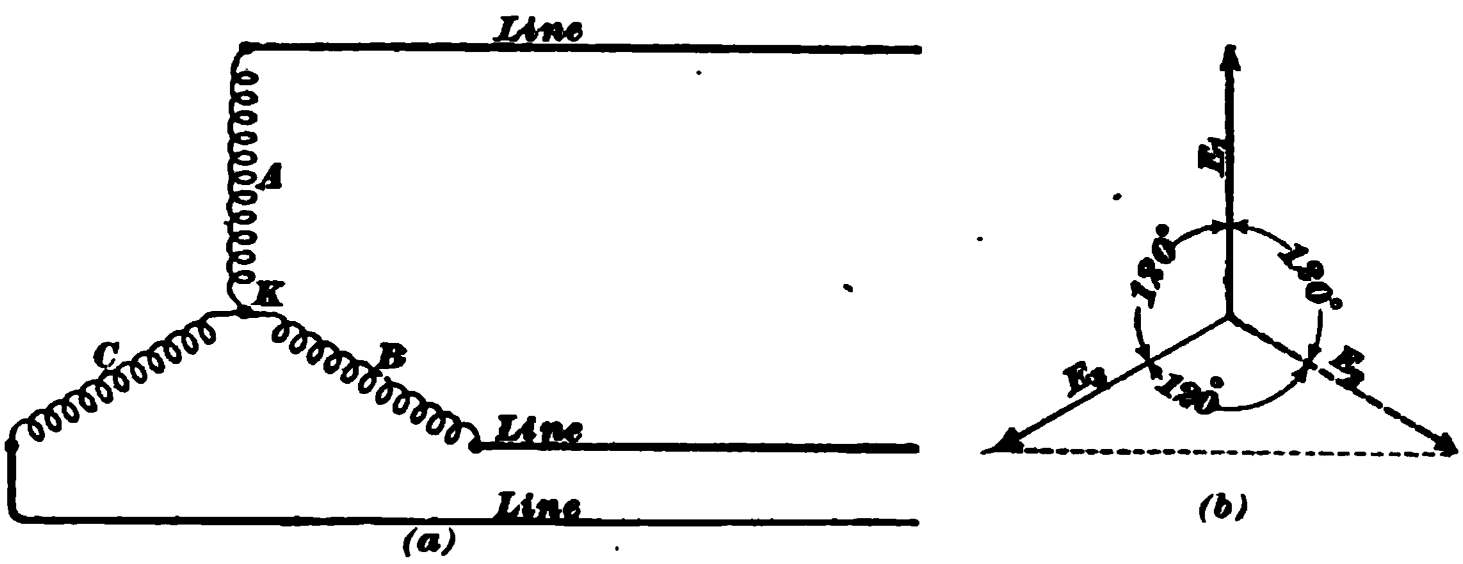


FIG. 37

the phases is joined to a common connection *K* and the other three ends are carried to three collector rings. This is a common method of connecting up three-phase armatures, known as the Y or **star connection.** The windings in Figs. 32 and 33 are shown connected up in this way. In connecting up the terminals *a*, *a'*; *b*, *b'*; *c*, *c'* to form a star winding, care must be taken to preserve the proper relation of the E. M. F.'s in the different sets of coils. When the E. M. F., in one set of coils is at its maximum, the E. M. F.'s in the other two sets are half as great and in the opposite direction. Suppose, then, that we take the instant when

set *A*, Fig. 33, is generating its maximum E. M. F. (conductors opposite centers of poles), and suppose that the E. M. F. in this set is directed away from the common junction *K*. Then terminal *a* will be connected to *K*. Since the current in the other two sets of coils is at the same instant one-half as great and in the opposite direction, they must be so connected that the current in them will be flowing toward the common junction. In order to satisfy this condition, the terminals *b* and *c* are connected to *K*. The remaining three terminals are connected to the collector rings *1*, *2*, and *3*.

38. Instead of connecting up the phases in the Y fashion, they may be formed into a closed circuit, as shown in

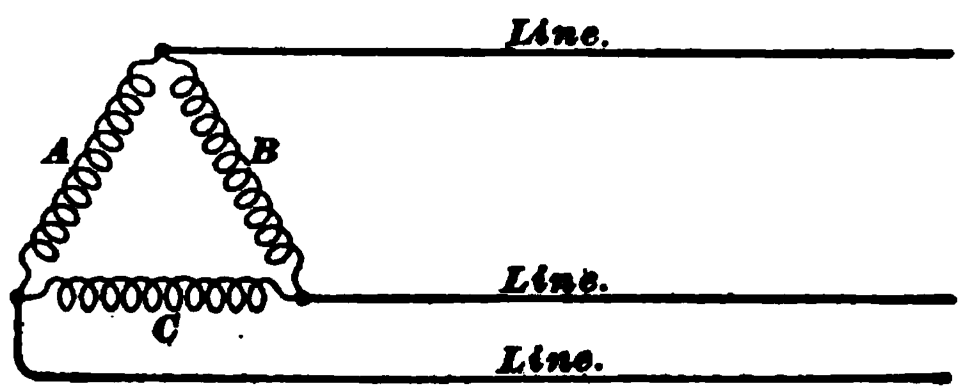


FIG. 38

Fig. 38, the collector rings being attached to the point where the phases join. This is known as the Δ (**delta**) or **mesh connection.** This method, like the last described, requires only three collector rings, and is extensively used.

Fig. 39 shows the same winding as Fig. 33 connected up Δ, and it will be noticed that there is no common connection, as in Fig. 33. The three sets of coils are connected up in series, as before, leaving the three pairs of terminals *a*, *a'*; *b*, *b'*; *c*, *c'*. We will consider the currents in the coils at the instant when the current in set *A* is at its maximum; that is, when the conductors are midway under the pole pieces. At this particular instant, the currents in the other two sets will be one-half as great and in such a direction that the sum of the currents taken around the closed circuit of the armature winding is zero. If the

maximum current is represented by I, the value and direction of the currents in the three sets of coils must be as shown

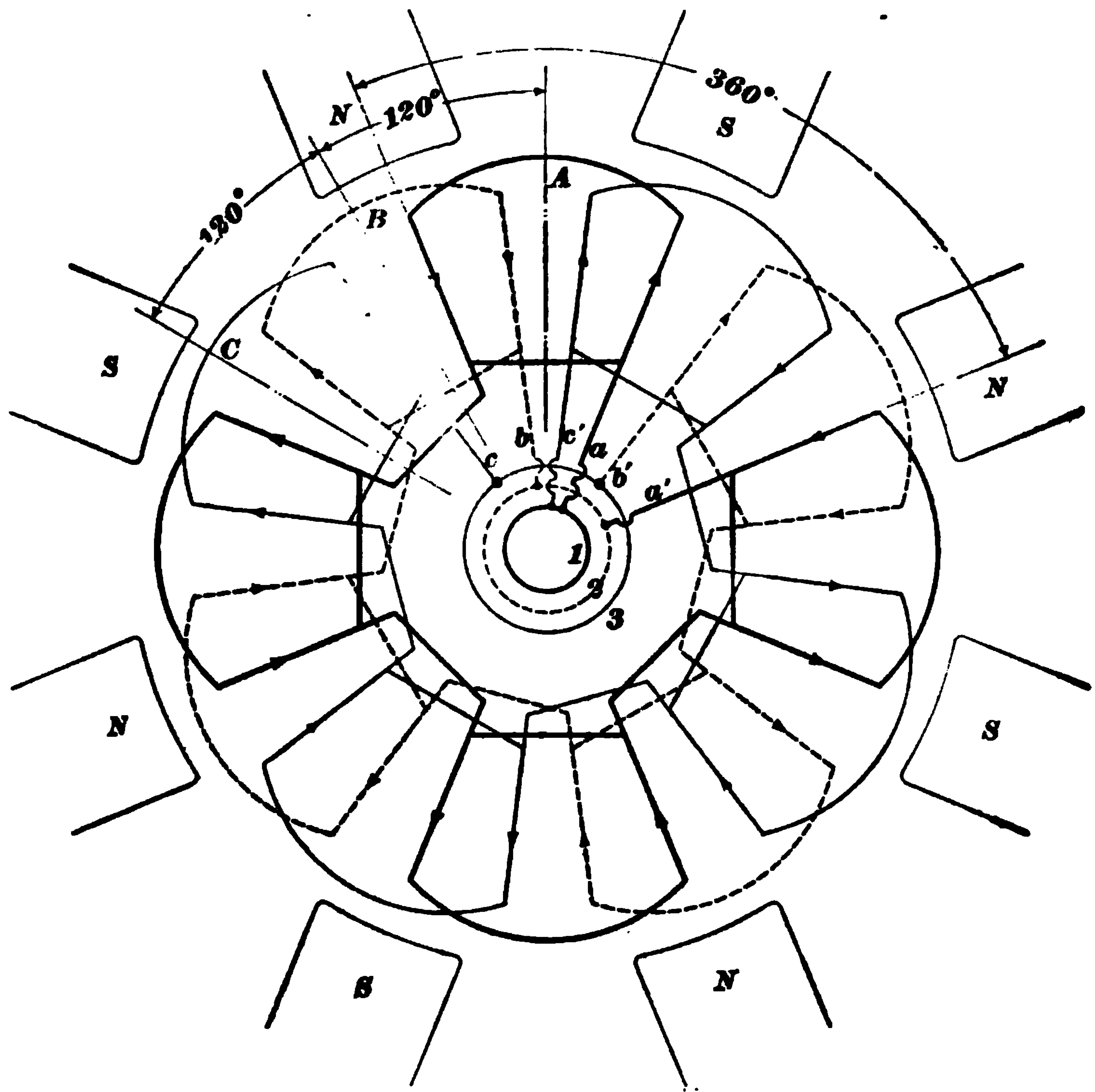


FIG. 39

in Fig. 40. Starting from one end of phase A, Fig. 39, by connecting a to the inner collector ring, we therefore pass

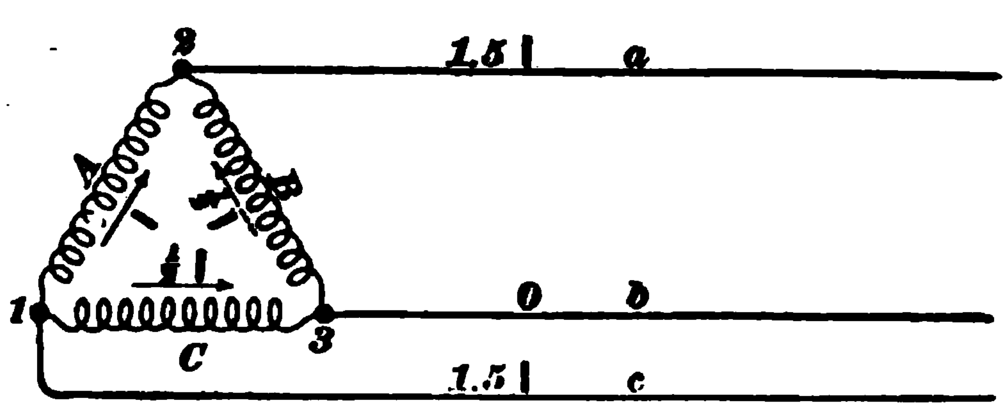


FIG. 40

through phase A in the direction of the arrows to the middle ring. From there we must pass through B against the

arrows; hence the terminal *b* must be connected to the middle ring and the other end *b'* to the outer ring. From the outer ring the current must pass through *C* against the arrows; hence, the terminal *c* must be connected to the outer ring and the other terminal *c'* carried to the inside ring.

39. Both of the above methods of connection are in common use not only for alternators, but also for synchronous motors and induction motors; it is, therefore, important to bear in mind the methods of connection and the distinction between them.

RELATION BETWEEN CURRENT, E. M. F., AND OUTPUT

40. The E. M. F. and current output of a three-phase alternator depends on the scheme that is adopted for connecting up the armature. Suppose the coils *A*, *B*, and *C*, Fig. 41, represent the windings of an armature Y connected.

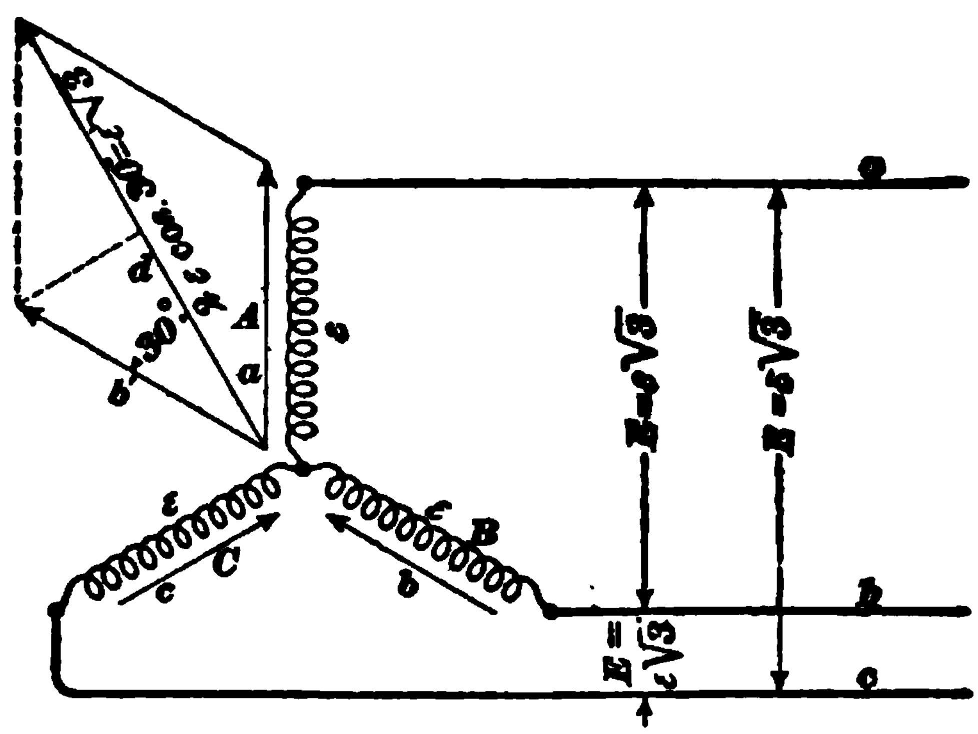


FIG. 41

Let ϵ be the effective value of the voltage generated in each phase. The volts obtained between the lines *a*, *b* will be the resultant of the two voltages ϵ in *A* and *B*. Let *E* represent the pressure between the lines. *E* must be equal to $2\ \epsilon \cos 30°$.

NOTE.—The resultant of the E. M. F.'s in coils *A* and *B*, which is the line E. M. F. *E*, may be found as follows: Represent the

E. M. F.'s in the three phases by the arrows a, b, c. Suppose the E. M. F. in A to be directed away from the common junction; then the E. M. F.'s in c and b will be directed toward the common junction. To add a and b we must draw b' from the extremity of a equal to and in the same direction as b. The resultant of a and b' will be d, which is the line E. M. F. E. The resultant d is equal to $2\,\varepsilon \cos 30° = \varepsilon\sqrt{3}$.

In a three-phase Y*-connected alternator, the voltage between any two collector rings is equal to the voltage generated per phase multiplied by $\sqrt{3}$ or 1.732.*

Conversely: *If the line voltage maintained by a three-phase* Y*-connected alternator is E volts, the voltage generated by each phase must be E divided by $\sqrt{3}$ or 1.732.*

41. It is easily seen from Fig. 41 that if we have a current I flowing in any of the lines, the current in the phase to which it is connected must also be I. Hence,

In a three-phase Y*-connected alternator, the current in the armature windings is the same as that in the line.*

42. The total output in watts will be the sum of the outputs of each of the three phases. The current in each of the three phases is I and the voltage is ε; hence, the total watts developed on a non-inductive load will be $3\,\varepsilon\,I$. But $\varepsilon = \frac{E}{\sqrt{3}}$. Therefore the total output $W = \frac{3\,E\,I}{\sqrt{3}} = \sqrt{3}\,E\,I$, where I is the current in the line, and E is the voltage between any pair of lines. Hence,

The output, in watts, of a three-phase Y*-connected alternator working on a non-inductive load is equal to $\sqrt{3}$ or 1.732 times the product of the line current and line E. M. F.*

43. For a Y-connected winding we may summarize the following formulas, in which

ε = volts generated per phase;
E = line voltage;
W = total watts output;
I = line current;
i' = current per phase or current in windings.

$$E = 2\,\varepsilon \cos 30° = \varepsilon\sqrt{3} \qquad (5)$$

$$\varepsilon = \frac{E}{\sqrt{3}} \qquad (6)$$

$$I = i' \qquad (7)$$

$$W = \sqrt{3}\,E\,I \qquad (8)$$

44. In case the armature is delta connected, as shown in Fig. 42, the E. M. F. ε generated in each phase is equal to

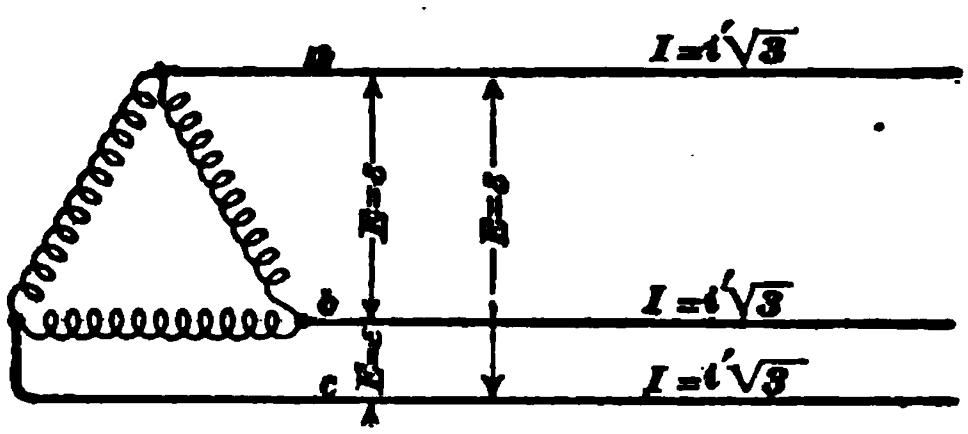


FIG. 42

the line E. M. F. E, because the different phases are connected directly across the lines. The current in the armature windings, however, is not as great as that in the lines, because it divides at each of the collector rings. If i' represents the current in each phase, the current in the lines will be $2\,i' \cos 30° = i'\sqrt{3} = 1.732\,i'$. The total watts output will be $3\,i'\,E = 3\frac{I}{\sqrt{3}}E = \sqrt{3}\,E\,I = 1.732\,E\,I$. Hence, it may be stated that

In a three-phase delta-connected alternator, the line voltage E is equal to the voltage generated in each phase.

In a three-phase delta-connected alternator, the current I flowing in the line is equal to the current i' in each phase multiplied by $\sqrt{3}$ *or 1.732.*

Conversely: *If the current flowing in the line is I, the current that the armature conductors must carry will be I divided by* $\sqrt{3}$ *or 1.732.*

The watts output of a three-phase delta-connected alternator working on a non-inductive load is equal to $\sqrt{3}$ *or 1.732 times the product of the line current and line E. M. F.*

45. The following formulas relating to a delta winding may then be summarized:

$$E = \varepsilon \qquad (9)$$

$$I = i' \sqrt{3} \qquad (10)$$

$$i' = \frac{I}{\sqrt{3}} \qquad (11)$$

$$W = E I \sqrt{3} \qquad (12)$$

46. It will be noticed that the expression for the watts output remains the same, whether the armature be connected **Y** or Δ. It follows, therefore, that the output of a three-phase armature is not altered by changing its connections from **Y** to Δ, or the reverse. The **Y** method of connection gives a higher line voltage than the Δ for the same E. M. F. generated per phase, while the Δ connection cuts down the current in the armature conductors. The **Y** winding is, therefore, best adapted for machines of high voltage and moderate current output, as it does not require such a high E. M. F. to be generated per phase. On the other hand, the Δ connection is more suitable for machines of large current output, as it keeps down the size of the armature conductors. The best style of winding for any given machine depends largely, therefore, on the work that it must do. These formulas regarding **Y** and Δ windings apply also to polyphase synchronous motors and induction motors described later. The formula $W = E I \sqrt{3}$ gives the output only when the load is non-inductive, i. e., power factor = 1, and balanced. If the load is inductive and balanced, the output is $W = \sqrt{3}\, E I \cos \phi$, where $\cos \phi$ is the power factor of the load.

EXAMPLE 1.—A three-phase alternator has a capacity of 100 kilowatts at a line pressure of 1,000 volts. What is the maximum line current that may flow in each of the three lines leading from the machine?

SOLUTION.—We have, from formula **8**,

$$W = \sqrt{3}\, E I, \text{ or } 100{,}000 = \sqrt{3}\, I\, 1{,}000$$

hence, $I = \frac{100{,}000}{1{,}000 \times \sqrt{3}} = 57.7$ amperes. Ans.

Example 2.—(*a*) If the above armature be Y connected, what will be the current in the armature conductors? (*b*) What must be the E. M. F. generated in each phase?

Solution.—(*a*) In a Y-connected machine, the current in the windings must be the same as the line current, that is, 57.7 amperes. Ans.

(*b*) From formula **6** we have

$$e = \frac{E}{\sqrt{3}} = \frac{1{,}000}{\sqrt{3}} = 577 \text{ volts. Ans.}$$

Example 3.—(*a*) If the same machine were changed to the delta connection, what would be the allowable maximum line current? (*b*) What would be the line voltage with a delta-connected armature?

Solution.—(*a*) The winding is such as to allow 57.7 amperes in each phase; hence, from formula **10**, we have

$$I = i' \sqrt{3} = 57.7 \sqrt{3} = 100 \text{ amperes} = \text{line current. Ans.}$$

(*b*) The line voltage E would be equal to e, and would be 577 volts. The total output would be $E I \sqrt{3} = 577 \times 100 \times \sqrt{3} = 100{,}000$ watts, or the same as with a Y winding. Ans.

47. It is seen, then, in the above example, that by changing the Y winding over to Δ, the current output has been increased from 57.7 amperes to 100 amperes, while the line E. M. F. has been decreased, in the same proportion, from 1,000 volts to 577 volts, the total watts, however, remaining the same.

48. The principal differences in the connections of multiphase armatures, as distinguished from single-phase, have been given in the preceding articles; as far as the mechanical construction goes there is no essential difference. Toothed armature cores with the coils or conductors bedded in slots are now almost universal in alternators as well as direct-current machines. Of course, polyphase windings give rise to a larger number of coils to dispose of, and, therefore, usually give more crossings of the conductors or coils at the ends of the armature; but polyphase armatures are constructed essentially in the same manner as those used for single-phase machines.

MONOCYCLIC SYSTEM

49. The **monocyclic alternator,** brought out by Steinmetz, is intended for use in stations where the greater part of the load consists of electric lights, but where it is also desired to have a machine capable of operating motors as well. In cases where the motor load is large, it is usual to use a regular two- or three-phase system. The monocyclic system is now seldom installed.

The monocyclic alternator is really a single-phase machine with a modified armature winding. The armature is provided with a set of coils constituting the main winding, the terminals of which are connected to the two outside collector rings, Fig. 43. In addition to this winding, a second set of coils is provided, which are placed on the armature 90° behind the main coils, in just the same way as shown for the two-phase machine, Fig. 25. This second set is unlike those in a regular two-phase machine in that the number of turns in the *teaser coils*, as they are called, is only one-fourth that of the main set, and one end of the teaser set is attached to the middle of the main winding, instead of being brought out to a collector ring. The other end of the teaser winding is brought to the middle collector ring, as shown in Fig. 43. This second winding furnishes an E. M. F. displaced 90° from the main E. M. F., and of one-quarter its value, thus furnishing an out-of-phase pressure suitable for starting motors. If it is desired to run lights

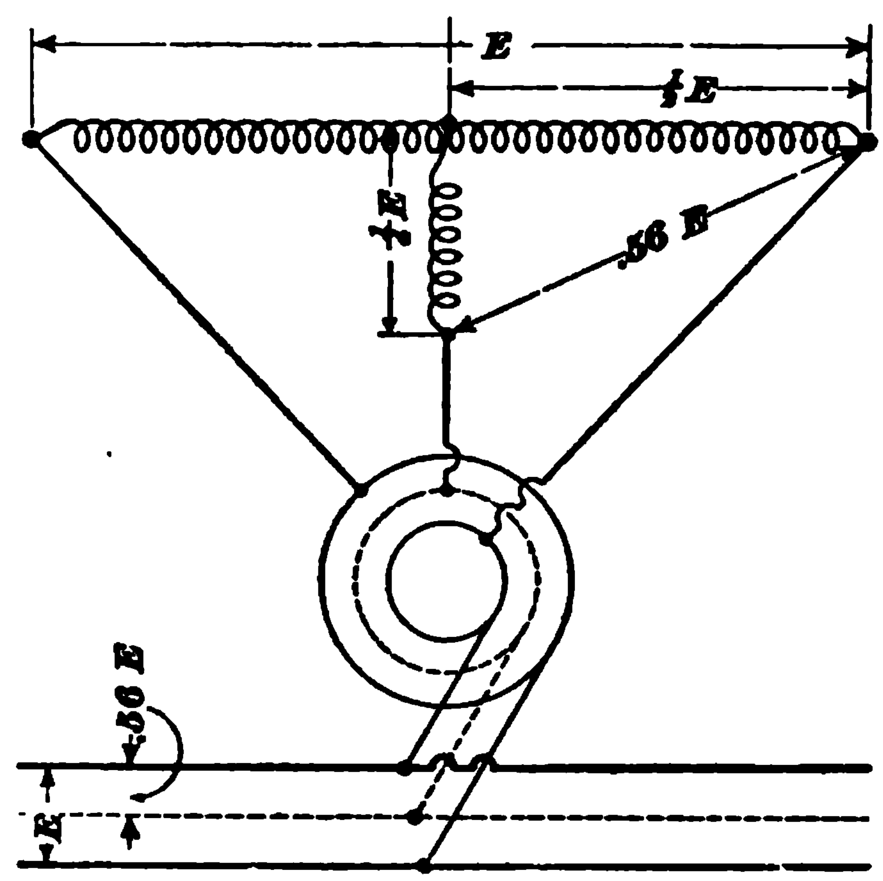


FIG. 43

only, the two outside wires alone are used, it being necessary to run the third wire only to places where motors are used. By referring to the figure, it will be seen that the E. M. F. between either of the outside and the middle rings is equal to $\sqrt{(\frac{1}{2}E)^2 + (\frac{1}{4}E)^2} = .56\,E$, nearly. For example, if the main winding generated 1,000 volts, the pressure between the middle and outside rings would be 560 volts, nearly.

ALTERNATORS WITH CLOSED-CIRCUIT ARMATURE WINDINGS

50. The windings for alternator armatures so far considered have for the most part been of the open-circuit type. The Δ-connected three-phase armature is an exception, since the windings in this case form a closed circuit. Consider an ordinary two-pole direct-current armature winding. If, instead of connecting this winding to a commutator we connect two diametrically opposite points to collector rings, we will have a single-phase alternator with a closed-circuit distributed winding having two paths in parallel. The current in the armature conductor would, therefore, be one-half the current in the external circuit, as in a regular two-pole direct-current dynamo.

If the closed circuit winding be tapped at four equidistant points, as shown in Fig. 44, and the terminals *1'*, *3'*, and *2'*, *4'*, connected to collector rings, the current obtained from *1'*, *3'* will be at right angles to that obtained from *2'*, *4'*, and a quarter-phase alternator will be the result. This style of winding has been used very extensively by the Westinghouse Company. If it is desired to operate a two-phase three-wire system from such a machine, three of the collector rings, or taps, are used; as, for example, *1'*, *3'*, *2'*. It is evident that no two of the taps could be connected together without short-circuiting a portion of the armature. If a three-wire two-phase system were operated from lines *1'*, *3'*, *2'*, one

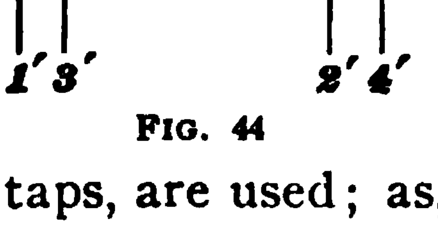


FIG. 44

phase would be between *1'* and *2'* and the other between *3'* and *2'*. Also, if the E. M. F. between *1'* and *3'*, i. e., the E. M. F. per phase with the four-wire arrangement were E, then the E. M. F. between *1'* and *2'* or the E. M. F. in the second case would be $\frac{E}{1.414}$. If a three-phase two-pole machine were required, the closed-circuit winding would be tapped at three equidistant points. For multipolar alternators with an ordinary multiple winding, there would be a tap to each ring for each pair of poles, as explained later in connection with rotary converters. With series-wound two-circuit multipolar armatures it would be necessary to have only one tap for each ring, the angular displacement of these taps depending on the number of poles and the number of phases.

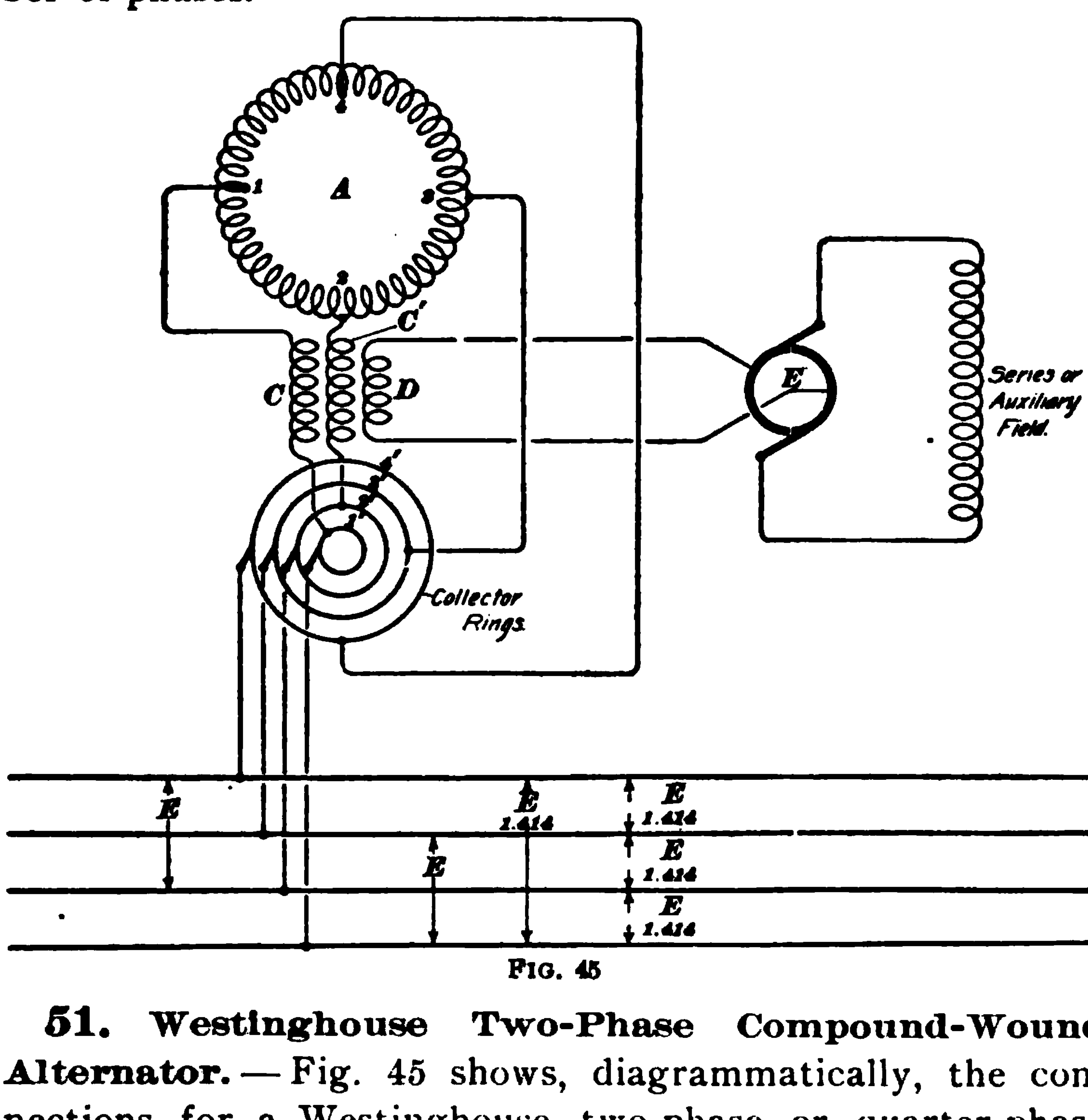


FIG. 45

51. Westinghouse Two-Phase Compound-Wound Alternator.—Fig. 45 shows, diagrammatically, the connections for a Westinghouse two-phase or quarter-phase

alternator with closed-circuit armature winding. The diagram is drawn for a two-pole machine in order to simplify it as much as possible. The winding *A* is tapped at the four equidistant points *1*, *2*, *3*, *4*, and these taps connected to the collector rings *1'*, *2'*, *3'*, *4'*: In series with one tap of each phase are the two primary coils *C*, *C'* of a revolving transformer mounted within the armature. The coils are wound on a core together with the secondary coil *D*, which is arranged so that the resultant magnetic flux produced

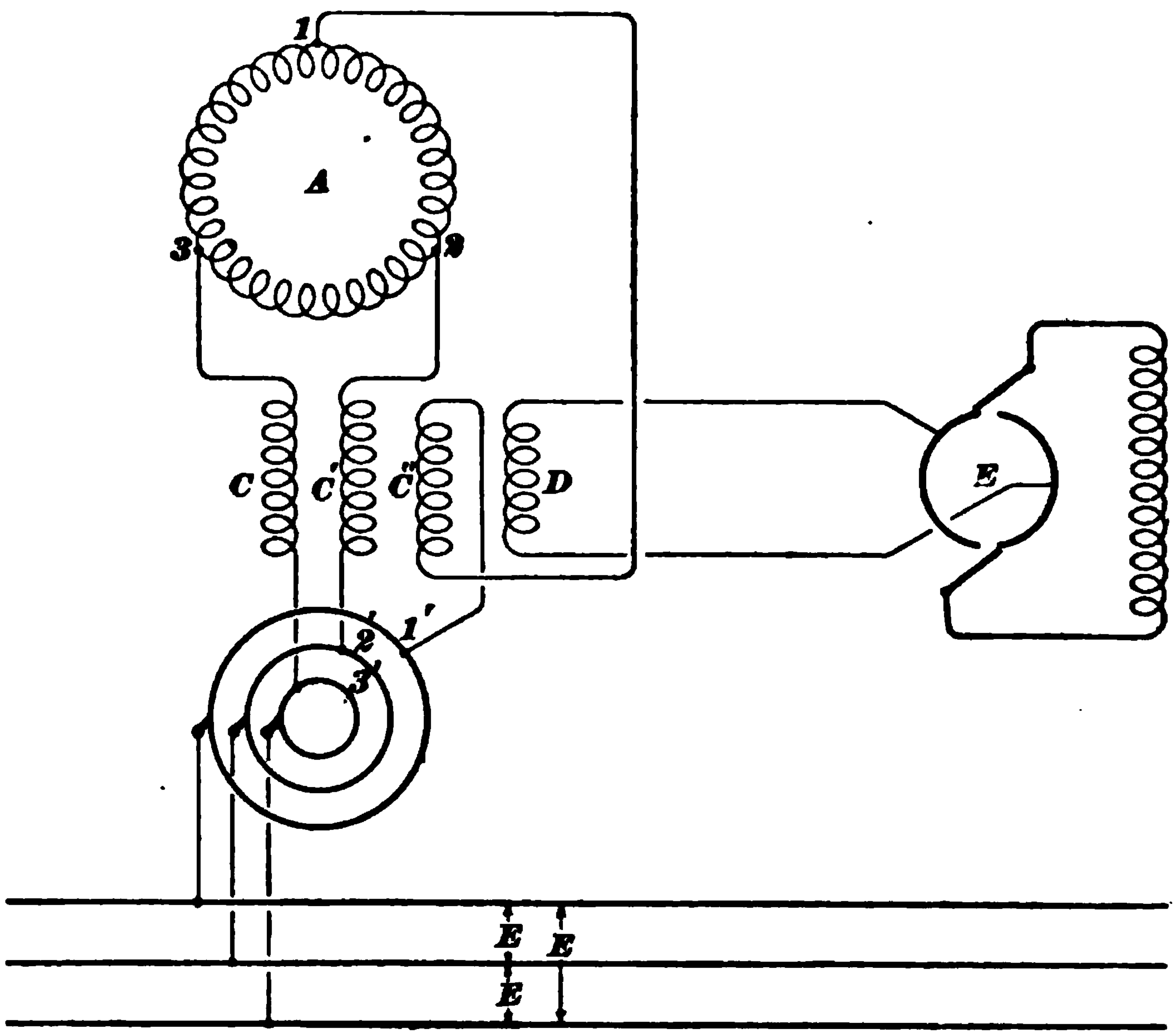


Fig. 46

by *C* and *C'* passes through *D*. The current induced in *D* is therefore proportional to the sum of the currents in the two phases. This current is rectified by means of the commutator *E* (which would have as many segments as the machine has poles), and passed around the series-field, thus strengthening the field as the load is applied. The separately excited winding is not indicated in the figure, as this is supplied with current in the usual manner from a separate exciter.

52. Westinghouse Three-Phase Compound-Wound Alternator.—Fig. 46 shows the connections for a Westinghouse three-phase compound-wound alternator. The method of compounding is similar to that shown in Fig. 45, except that the series-transformer carried within the armature has three primary coils C, C', C'', connected in series with the leads as shown. The resultant flux induces a secondary current proportional to the sum of the loads on the different phases, and this current is passed through the auxiliary coils after being rectified.

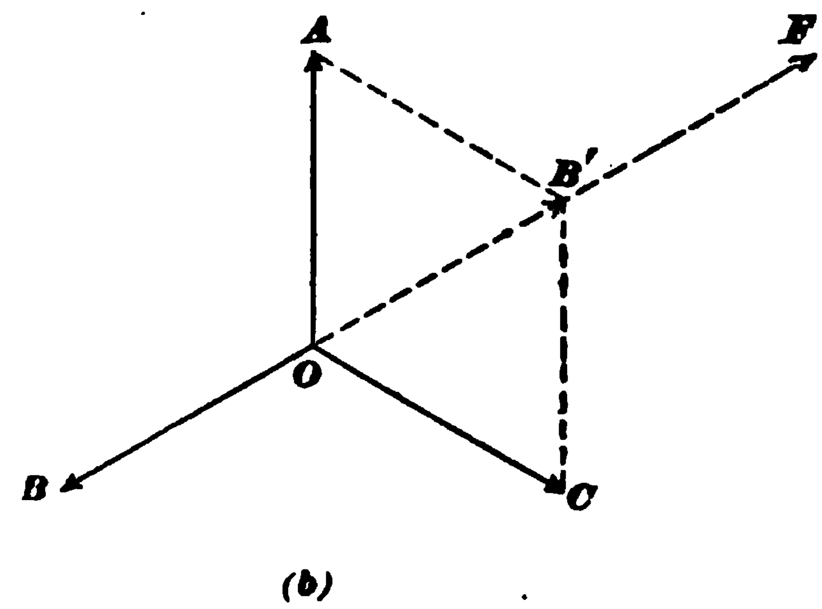


Fig. 47

It should be noticed in Fig. 46 that the connections to one of the secondaries are reversed. The reason of this is that the resultant flux produced by three currents OA, OB, OC, Fig. 47, differing 120° in phase would be zero. If one of the coils is reversed, three fluxes OA, OB', OC differing by 60° are the result, and these three produce the resultant flux OF.

ALTERNATING-CURRENT APPARATUS

TRANSFORMERS

1. One of the principal reasons why direct current is giving place so largely to alternating is the ease with which the latter may be transmitted over long lines at high voltages, and then be transformed at the receiving end to currents of lower pressure suitable for operating lights, motors, or other devices. If power is to be transmitted over long distances by means of the electric current, it is absolutely necessary that high line pressures be employed, in order to make the cost of the conductors reasonably low. For a given amount of power transmitted, the current will be smaller the higher the pressure employed. The loss in the line, however, increases with the square of the current; consequently, if the pressure on a line be doubled, it means that, with the same loss, only one-fourth the amount of copper will be required in the conductors. In other words, with a given amount of power to be transmitted and a given fixed amount of loss, the copper required will decrease as the square of the voltage increases. By using high pressures, it is evident that a small line conductor may be made carry a large amount of power over a long distance, and still not have the loss any greater than if a low pressure and a very large and expensive conductor had been employed.

2. Transmission with direct current at high pressure has never been used to any large extent in America, though some plants of considerable size are in operation in Europe. This is principally because of the difficulty of building direct-current machines to generate the high E. M. F.'s necessary. The commutators on such high-tension machines are apt to give trouble, and, moreover, it is difficult to transform the high-tension direct currents at the other end of the line down to currents at pressures suitable for ordinary use. The alternating current is open to neither of these objections, because an alternator has no commutator to give trouble, and high-tension alternating currents may easily be transformed down. Devices used for changing an alternating current of one voltage to another of higher or lower voltage are known as **transformers.** Transformers may be used either to *step-up* the voltage, i.e., increase it, or they may be used to *step-down*, or decrease, the line pressure. Whether the transformer be used to step up or down, the change in pressure is always accompanied by a corresponding change in the current, and the power delivered to the transformer is always a little greater than that obtained from it. For example, suppose a current of 20 amperes were supplied to a transformer from 1,000-volt mains. If the load on the transformer were non-inductive, the E. M. F. and current would be almost exactly in phase, and the watts supplied to the side connected to the mains (primary side of the transformer) would be $20 \times 1{,}000$, or 20,000 watts. The power obtained from the secondary side, or the side connected to the circuit in which the power is being used, would not be quite as much as this. Suppose the secondary E. M. F. were 100 volts; if there were no losses in the transformation, we would obtain 20,000 watts from the secondary, and the available secondary current would be $\frac{20000}{100} = 200$ amperes. In other words, the decrease in E. M. F. has been accompanied by a corresponding increase in current. As a matter of fact, there is always some loss in conversion, and the secondary output is never quite equal to the power supplied to the primary.

The ratio $\frac{\text{watts output}}{\text{watts input}}$ gives the efficiency of the transformer. A good transformer is one of the most efficient pieces of apparatus known, some of large size delivering as much as 98.5 per cent. of the energy supplied.

3. Transformers used for changing an alternating current at one pressure to another alternating current at another pressure are often called **static transformers,** because they have no moving parts. This is done to distinguish them from **rotary transformers,** or **rotary converters,** which are used to transform alternating current to direct, or vice versa. Such machines always have moving parts, hence their name.

4. Nearly all transformers are operated on constant-potential systems. The transformer is supplied with current from mains, the pressure between which is kept constant, and this current is transformed to one of higher or lower pressure, the secondary pressure also being constant or nearly so.

THEORY OF THE TRANSFORMER

5. A simple transformer is shown in Fig. 1. C is a laminated iron ring, on which are two coils P and S. The coil P has a number of turns T_p, and S has, we will suppose, a smaller number of turns T_s. The coil P is the *primary*, and is connected to the alternator mains across which the constant pressure E_p is maintained. Coil S, from which current is delivered, is called the *secondary*. We will suppose, for the present, that the resistance of both primary and secondary coils is negligible. The above is essentially the construction of the ordinary static transformer. It consists of two coils or sets of coils interlinked by an iron magnetic circuit.

Suppose a voltmeter V be connected to the terminals of the secondary coil S. The resistance of the voltmeter is

very high; consequently, a very small current will flow through the secondary, and we may, for all practical purposes, consider the secondary as on open circuit with no current flowing. The line E. M. F. E_p will cause a current to flow through the primary coil, and this current will set up an alternating magnetic flux in the iron core. This alternating flux will set up a counter E. M. F. in the coil P, which will be the equal and opposite of E_p, since the coil is

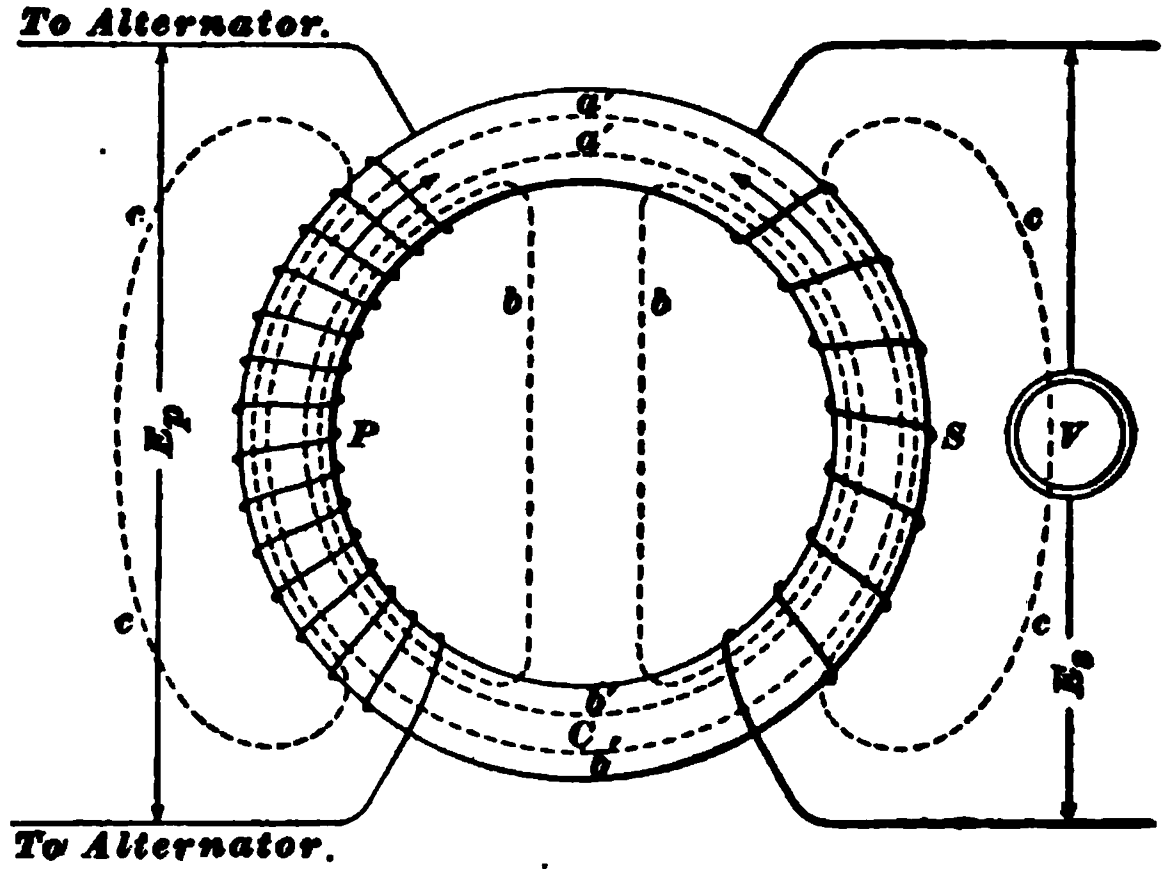


FIG. 1

supposed to have no resistance. If the maximum magnetic flux be Φ and the number of cycles per second n, we will have

$$E_p = \frac{4.44\ \Phi\ T_p\ n}{10^8}$$

The current that will flow in the primary when the secondary is on open circuit is that current which is required to set up a magnetic flux Φ capable of producing a back E. M. F. equal and opposite to the applied E. M. F. Since the coil P is provided with a closed iron circuit, it is evident that a very small current is able to set up a large magnetic flux; hence, the current required when the secondary is on open circuit may be, perhaps, only a fraction of an ampere. In other words, the applied E. M. F. is capable

of forcing only a small current through the primary, on account of its high self-induction.

6. The flux Φ set up by the primary coil also interlinks the secondary S, and as it is continually alternating through it, an E. M. F. will be set up in the secondary coil, which will be

$$E_s = \frac{4.44\ \Phi\ T_s n}{10^8}$$

and

$$\frac{E_p}{E_s} = \frac{T_p}{T_s} \qquad (1)$$

or

$$E_s = E_p \frac{T_s}{T_p} \qquad (2)$$

7. The ratio of the primary voltage to secondary, i. e., $\frac{E_p}{E_s}$, is called the **ratio of transformation.** It also follows from the above that the ratio of transformation is equal to the primary turns divided by the secondary turns. For example, if a transformer be supplied with 1,000 volts primary and has 500 turns on its primary coil while there are 50 turns on the secondary, the ratio of transformation is 10, and the secondary voltage $1{,}000 \times \frac{50}{500} = 100$ volts. In this case the transformer reduces the voltage from 1,000 to 100, but the operation could be reversed, that is, it could be supplied with 100 volts and the pressure raised to 1,000.

8. It was assumed above that all the magnetic flux Φ that threaded the primary coil also passed through the secondary, and in well-designed transformers this is nearly the case. However, some lines may leak across, as shown by the dotted lines b, b, c, c, without passing through both coils. This is known as **magnetic leakage,** and its effect on the action of the transformer will be noticed later.

9. So far, in dealing with the action of the transformer, the secondary has been supposed to be on open circuit. It is now necessary to examine the transformer action when

the secondary is working on a load. While the construction of a transformer is exceedingly simple, the reactions that occur when it is loaded are by no means so simple, and for the sake of clearness we will first examine the action of an ideal or perfect transformer—one that has no resistance in its coils, no magnetic leakage, and no hysteresis or eddy-current loss in its core. Such a transformer would have an efficiency of 100 per cent., and after examining its workings we can easily note the effect of the introduction of one or more of the above defects, which are present to a greater or less extent in all commercial transformers. The fact that the efficiency of good transformers is commonly over 95 or 96 per cent., and even rises to over 98 per cent., shows at once that the combined effect of all the above defects does not change the performance of the transformer very much from that of the ideal.

10. In the first place, if the core reluctance were zero, the current, with open-circuit secondary, necessary to set up the magnetic flux would be infinitely small. All cores have, however, some reluctance; hence, the effect of reluctance in the core is to increase this no-load current, or **magnetizing current**, as it is called. Since this magnetizing current is that which is caused to flow against the self-induction of the primary, it follows that it is a wattless current 90° behind the E. M. F. of the mains. It is important to keep the magnetizing current as small as possible; therefore, the magnetic circuit should be made short and of ample cross-section.

11. We have seen that the primary induces an E. M. F. $E_s = E_p \frac{T_s}{T_p}$ in the secondary at no load. Now, if the secondary circuit be closed, say through a non-inductive resistance made up of a number of incandescent lamps, a current will flow that will be in phase with the secondary E. M. F. When a transformer delivers current from its secondary, this secondary load current is directly opposite

in phase to the load current in the primary. Action and reaction are always equal and opposite, and the counter secondary current represents the reaction against which the primary current works when the transformer is loaded. Whenever a current I_s is taken from the secondary, a corresponding current I_p flows in the primary. The total current in the primary will, therefore, be made up of two components, one of which is the magnetizing current m and the other I_p, due to the current I_s in the secondary. The magnetizing power of the primary and secondary coils is proportional to their ampere-turns, that is, to $T_p\, I_p$ and $T_s\, I_s$, respectively. The load currents I_p and I_s are opposed to each other; hence, the total magnetizing effect of these two currents is

$$T_p\, I_p - T_s\, I_s$$

Now the input $E_p\, I_p$ is equal to the output $E_s\, I_s$ for an ideal transformer, or

$$I_p = I_s \frac{E_s}{E_p} = I_s \frac{T_s}{T_p} \qquad (3)$$

hence, we may write the total magnetizing effect of the two currents,

$$I_s \frac{T_s}{T_p} T_p - I_s\, T_s = 0 \qquad (4)$$

That is to say, when a current I_s is taken from the secondary of an ideal transformer, the corresponding current I_p that flows in the primary over and above the magnetizing current m is $I_s \frac{E_s}{E_p}$, and the total magnetizing effect of the two currents is zero. This means that the flux Φ in the iron core will remain constant, no matter what load is placed on the secondary.

12. Since the magnetic flux is constant for all loads, it follows that the secondary induced E. M. F. will also be constant, and if the secondary coil has no resistance, the E. M. F. at its terminals, that is, the secondary line E. M. F.,

will not change as the load is applied. An ideal transformer would, therefore, if supplied with a constant primary pressure, maintain the voltage between the secondary lines constant at all loads. This condition is approached quite closely in the best makes of modern transformers, the variation in secondary voltage being not more than 1.5 to 2 per cent., depending on the size. It is thus seen that while the transformer is most simple in construction, it adjusts itself exceedingly well to changes in load so as to maintain the desired constant secondary pressure, the whole automatic regulation being brought about by the interactions of the currents in the primary and secondary coils.

ACTION OF IDEAL TRANSFORMER

13. The action of a transformer without resistance, magnetic leakage, hysteresis, or eddy-current losses may be represented by Fig. 2, when working with an *open-circuit secondary*. Let $O\ N$ represent the magnetic flux; then the magnetizing current will be in phase with $O\ N$, and hence may be represented by $O\ m$. This current is 90° behind the primary impressed E. M. F. E_p, and E_p will, therefore, be represented by the line $O\ E_p$, 90° ahead of $O\ m$. The secondary E. M. F. E_s will be directly opposite in phase to E_p, and will be represented by $O\ E_s = E_p \frac{T_s}{T_p}$. In this case the transformer takes the small current $O\ m$ from the line, and since this current is at right angles to the E. M. F., it is wattless, $\cos\phi = 0$ and $E_p\ m \cos\phi = 0$, and the transformer consumes no energy. If the reluctance of the magnetic circuit

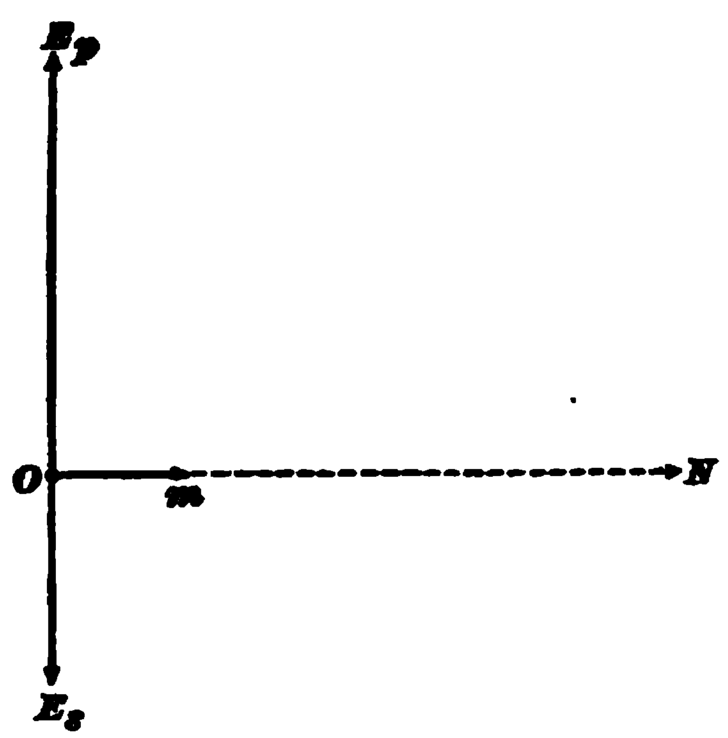


FIG. 2

were negligible, the magnetizing current $O\ m$ would be very small. However, in these diagrams its length has been exaggerated with respect to the lines representing the other currents, in order to illustrate the action more clearly.

14. When the secondary is connected to a non-inductive resistance, a current I_s flows in the secondary, and the action of an ideal transformer in this case is represented by Fig. 3. The lines $O\ N$ and $O\ m$ represent the magnetic flux and the magnetizing current, as before. $O\ E_p$ is drawn to scale to represent the primary E. M. F., and $O\ E_s$ represents the

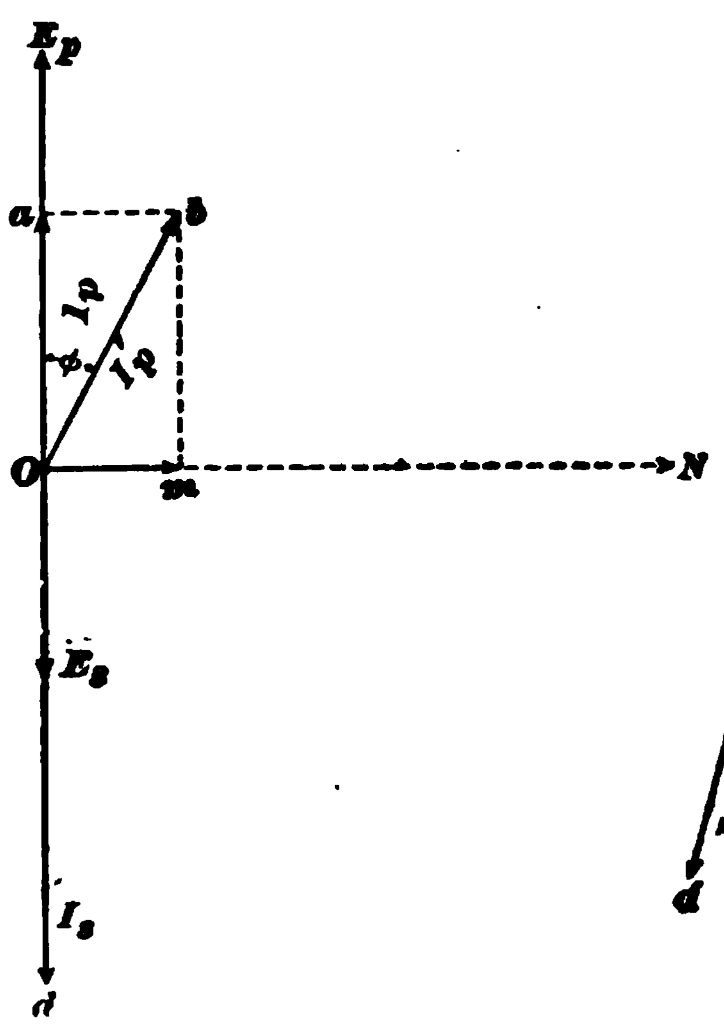


FIG. 3

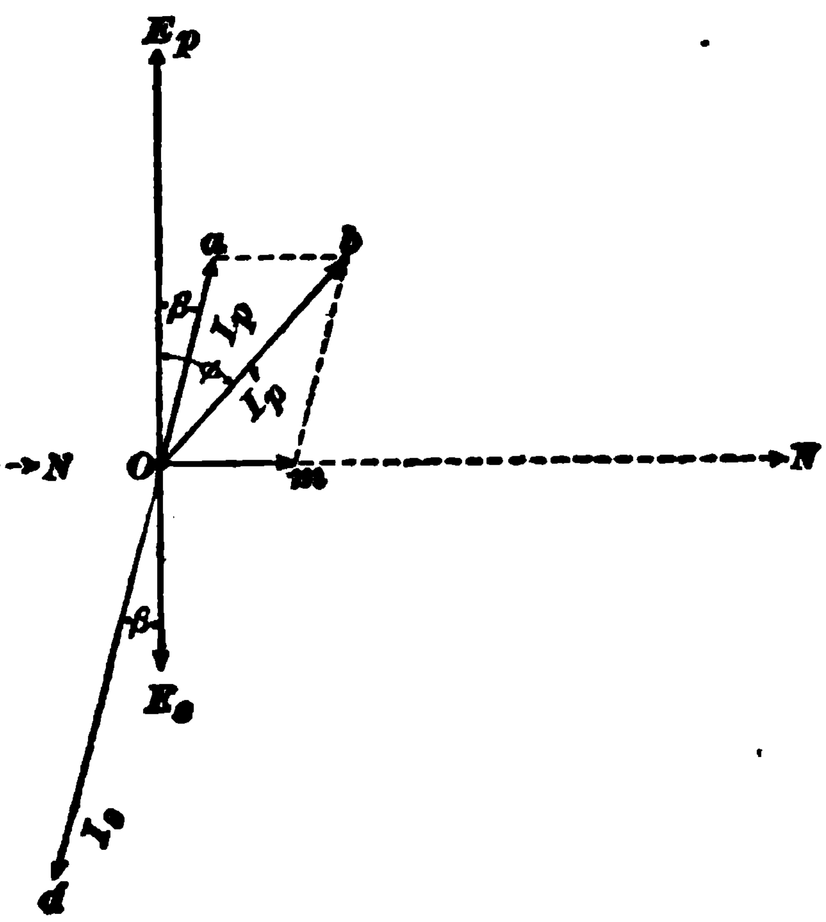


FIG. 4

secondary E. M. F. Let R be the resistance of the non-inductive circuit to which the secondary is connected; then the secondary current will be $I_s = \frac{E_s}{R}$, since the resistance is non-inductive, and may be represented to scale by the line $O\ d$ in phase with $O\ E_s$. The load current in the primary corresponding to I_s in the secondary will be $I_p = I_s \frac{T_s}{T_p}$ and

may be represented by the line $O\ a$ opposite in phase to $O\ d$ and representing I_p to the same scale that $O\ d$ represents I_s. In the case shown, $E_s = \frac{1}{2} E_p$; hence, $O\ a$ must be one-half the length of $O\ d$. The total current flowing in the primary will be the resultant of $O\ a$ and $O\ m$, or $O\ b = I'_p$. This resultant current lags $\phi°$ behind the impressed E. M. F., and it is evident that the more the transformer is loaded, the smaller ϕ becomes, and the nearer the primary current gets into phase with the primary E. M. F. In other words, taking current from the secondary acts as if it decreased the self-induction of the primary, thus allowing a larger current to flow. Since ϕ decreases as the load is applied, it follows that $\cos \phi$ increases; hence, the power supplied to the primary increases.

15. If the secondary of an ideal transformer furnishes current to an inductive load, such as motors, the secondary current I_s lags behind the E. M. F. E_s by an angle β of such amount that $\tan \beta = \frac{2 \pi n L}{R}$, where L is the inductance of the circuit and R the resistance. This action is represented by Fig. 4. The magnetizing current $O\ m$, magnetic flux $O\ N$, primary E. M. F. E_p, and secondary E. M. F. E_s are all represented as before. The secondary current I_s, however, lags behind E_s by the angle β; consequently, the corresponding primary load current $O\ a$ is behind the primary E. M. F. E_p by the same angle β, because I_p is opposite in phase to $O\ d$. The total primary current, being the resultant of $O\ m$ and $O\ a$, will be $O\ b$, lagging $\phi°$ behind E_p. It will be noticed that ϕ is greater than it would be if the transformer were working on a non-inductive load; hence, the primary current corresponding to a given output will be greater with an inductive load.

The above diagrams represent the action of an ideal transformer, and, as mentioned before, actual transformers approximate quite closely to the ideal. We will now notice what effect the resistance of the coils, core losses, and magnetic leakage have on the action of an actual transformer.

EFFECT OF RESISTANCE OF PRIMARY AND SECONDARY COILS

16. Transformer coils always have an appreciable resistance; hence, there will be a loss in them proportional to the square of the current. One effect, therefore, of coil resistance is the heating under load and a lowering of the efficiency. A transformer with an excessive amount of coil resistance cannot have a high efficiency. The resistance also produces another effect that is more detrimental than the mere loss in efficiency, namely, bad regulation. When a transformer regulates badly, the secondary E. M. F., instead of remaining nearly constant, drops off as the load is applied and rises when it is removed. This is a particularly bad feature, especially when incandescent lights are being operated, because the changes in voltage not only affect the brilliancy of the lamps, but also shorten their life. The resistance of the primary prevents the induced back E. M. F. from being quite equal to the line E. M. F., because a certain part of the impressed voltage is used in overcoming the resistance; this, in turn, will also cause the secondary induced E. M. F. to be slightly smaller than it would be if the primary had no resistance. The E. M. F. obtained at the terminals of the secondary will be further reduced by the drop due to the secondary resistance. It is thus seen that the general effect of the resistance is to cause a falling off in the secondary voltage when the transformer is loaded. The only way to prevent bad regulation from this source is to make the resistance of the coils as low as possible without making the design bad in other respects.

EFFECT OF MAGNETIC LEAKAGE

17. When a transformer has a large magnetic leakage, quite a number of the lines that pass through the primary will not thread the secondary; consequently, the E. M. F,

induced in the secondary will not be as large as it should be. Take the case of a transformer constructed as shown in Fig. 1. When it is not loaded, there is no current in the secondary coil, and consequently there is nothing to oppose the primary coil setting up lines through the magnetic circuit. Under these circumstances there would be very little leakage. When, however, a current flows in the secondary, a counter magnetic flux is set up that is opposed to the original flux set up by the primary, as indicated by the arrows. There is then a tendency for poles to form at a', a' and b', b', thus causing leakage lines $b\ b$ and $c\ c$ to be set up. Evidently the leakage will increase as the load on the secondary increases; hence, the tendency of magnetic leakage is to cause a falling off in the secondary voltage as the transformer is loaded. The effect of both resistance and magnetic leakage is, therefore, to produce bad regulation.

18. Magnetic leakage can be avoided to a large extent by so placing the coils with reference to each other that all the lines passing through one must pass through the other. This might be done by winding the two coils together, but this plan would not work in practice, owing to the difficulty of maintaining proper insulation between them. The type shown in Fig. 1 would have a large amount of leakage and would not be used in practice. A much better arrangement would be to wind the coils one on top of the other, thus leaving very little space for lines to leak through between them, or to wind the primary and secondary in sections and interleave them. Transformers in which this is done will be illustrated later.

EFFECT OF CORE LOSSES

19. Since the magnetism in the core is constantly changing, there will be a hysteresis loss, just as there is a

loss due to the varying magnetization of an armature core. The transformer will have to take power from the line to make up for this loss, thus lowering the efficiency. The amount of loss due to hysteresis depends on the quality and volume of iron in the core as well as on the maximum magnetic density at which it is worked. Since the magnetic flux Φ is nearly constant for all loads, the magnetic density must also be constant, and the hysteresis loss must be about the same, no matter what load the secondary is carrying. Heat losses also occur in transformer cores, due to eddy currents set up in the iron. The iron in the core acts as a closed conductor, and the alternating field induces small E. M. F.'s, which give rise to currents in the core. In order to prevent the flow of eddy currents, the core is laminated or built up of sheets varying in thickness from .014 inch to about .025 inch, depending on the frequency, the thicker iron being used for transformers designed to work on low frequencies. The effect of both eddy-current and hysteresis losses is simply to increase the power that the primary takes from the line, and thus lower the efficiency. These losses do not affect the regulation to any appreciable extent, but if large they may lower the efficiency considerably.

20. It has been shown above that the core losses take place as long as the primary pressure is maintained, and are about the same whether the transformer is doing any useful work or not. In many lighting plants, the line pressure is maintained all day, while the load may be on for only a few hours out of the twenty-four. It follows, therefore, that the I^2R, or copper, losses take place for a short time only, whereas the iron losses go on all day. In such cases it is important that the iron losses be small as compared with the copper losses, because, if this is not so, the transformer will have a low *all-day efficiency;* that is, it will give out a small amount of energy during the day compared with the amount it consumes.

CONSTRUCTION OF TRANSFORMERS

21. Transformers are made in a variety of forms, but they may, for convenience, be divided into two general classes: (1) *Core transformers;* (2) *shell transformers.*

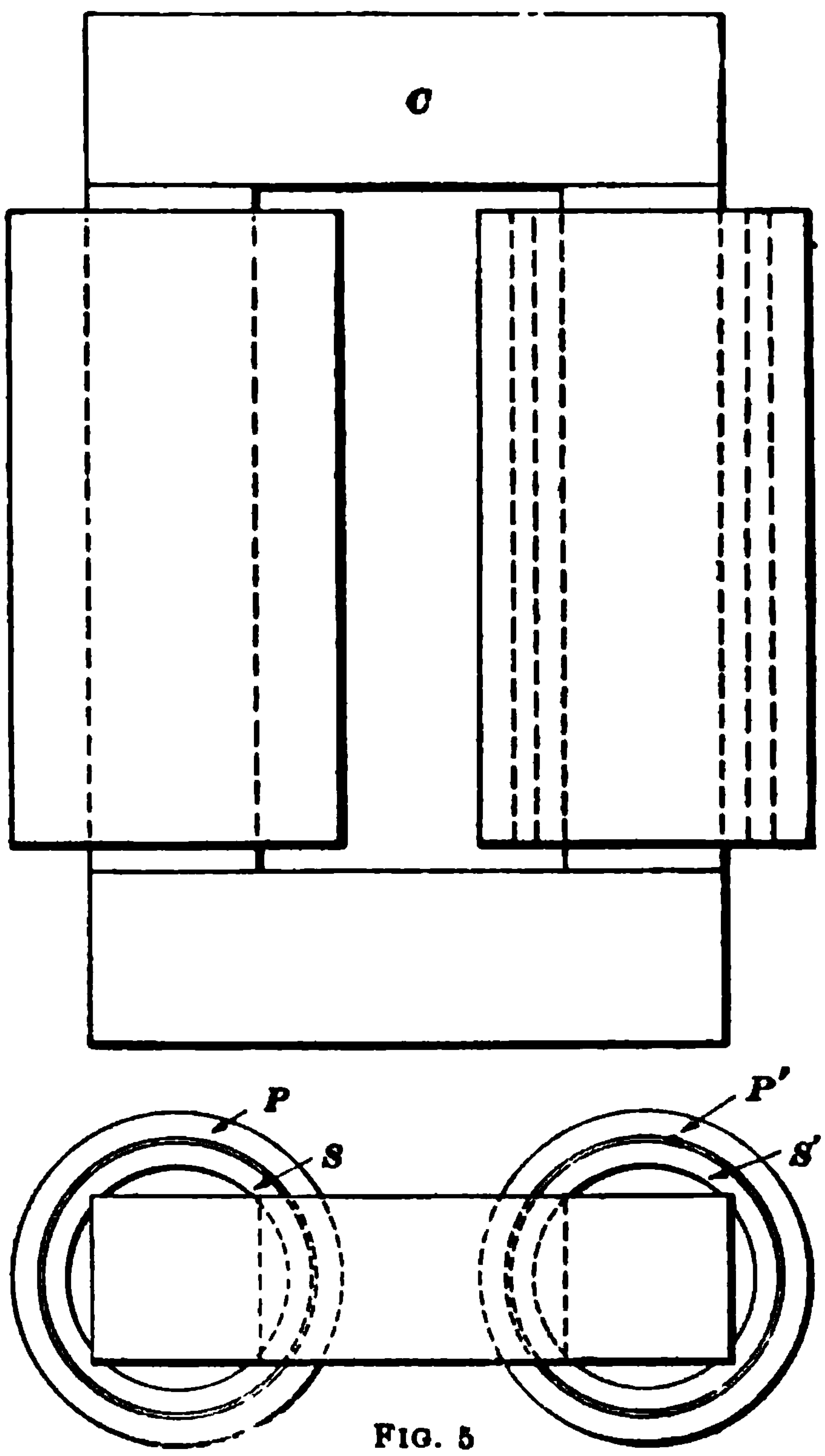


Fig. 5

In **core transformers,** the iron part forms a core on which the coils are wound, while in **shell transformers** the iron surrounds the coils. Figs. 5 and 6 show the arrangement of the parts of a common type of core transformer. The core *C*, Fig. 5, is built up of thin iron strips into the rectangular form shown; *P*, *P'*, *S*, *S'* are the primary and secondary coils, each wound in two parts. It will be noticed that the primary is wound over the secondary, thus making the leakage path between the coils long and of small cross-section, thereby reducing the magnetic leakage. Fig. 6 shows a section of the coils and core. One advantage of this type is that the core may be built up of strips of iron, no special stampings

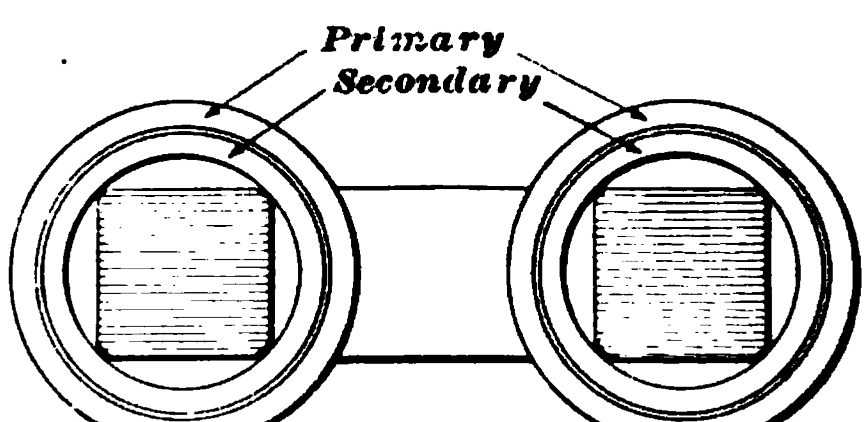


Fig. 6

being required. There is also an advantage in having the coils wound in two sections, in that it enables the transformer to be connected up for a variety of voltages.

EXAMPLES OF TRANSFORMERS

22. Fig. 7 shows a small 2-kilowatt Westinghouse transformer removed from its case. This transformer belongs to the so-called shell type, because the iron core is arranged so as to surround the coils. The iron stampings are shaped

FIG. 7

so that they can be easily slipped into place, and the joints overlap so that there is practically no break in the magnetic circuit; the various shapes of stampings used for

transformer cores will be considered in connection with transformer design. In this case, the primary is wound in two coils *P*, *P*, Fig. 8, and the secondary coil *S* is placed between the two in order to reduce the magnetic leakage between primary and secondary. The terminals of the primary are connected to the posts *t*, *t*, *t*, *t*, Fig. 7, and by means of the pieces *l* the coils can be

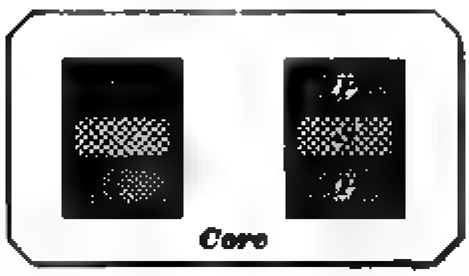


FIG. 8

FIG. 9

connected either in series or in parallel, so as to adapt the primary to either 1,050 or 2,100 volts. The secondary

coil is also provided with a number of terminals, so that secondary voltages of 52½, 105, or 210 volts may be obtained. Fig. 9 shows a larger size of Westinghouse transformer. This is also of the shell type and has a capacity of 575 kilowatts. It is intended for use in

Fig. 10

connection with substations where a large transformer is required. The flat coils are spread apart where they project from the core, so that the heat developed in the windings may be readily dissipated. Fig. 10 shows a section of a transformer of the same type as Fig. 7, but of larger size, mounted in its case and immersed in oil.

23. The General Electric Company's type **H** transformer is a good example of the core type. The general arrangement of the coils and core is shown in Figs. 5 and 6. Fig. 11 shows the shape of the core and the arrangement of the coils in the larger sizes. The core A is built up of straight iron strips of two different widths. This leaves openings or ducts a at each corner for the oil, in which the transformer is immersed, to circulate through. An annular space b is also left between the coils c, d, the object being to secure thorough insulation and a free circulation of oil so as to keep all parts of the coil and core at approximately the same temperature and thereby avoid strains on the insulation due to unequal expansion and contraction. The use of oil in transformers not only insures better insulation but it conducts the heat from the various parts to the outer case and thus makes the transformer run cooler. Fig. 12 shows the style of cast-iron case used for holding type **H** transformers of moderate size which are usually mounted outdoors. The case is oil and water-tight and the primary leads a, b and the secondary leads c, d, e, f, are brought out through porcelain insulating bushings.

FIG. 11

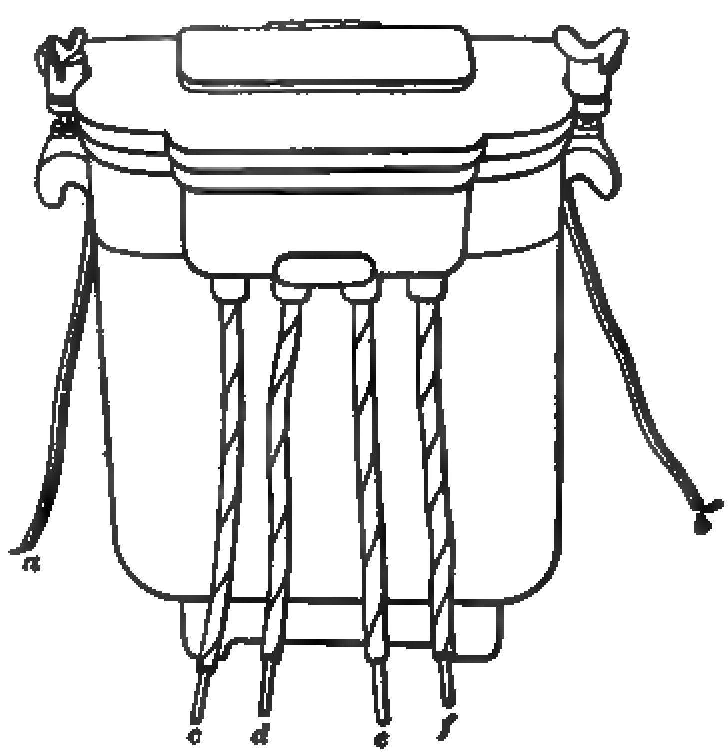


FIG. 12

Substation transformers of large size must usually be provided with artificial means for cooling, which will be described later in connection with substations.

24. Autotransformer.—Sometimes a transformer having but one winding, which serves both for the primary and secondary coils, is used for special purposes. A device of this kind is known as an **autotransformer.** In Fig. 13, A represents a laminated iron core on which two coils having turns t, t' are wound. These two coils are connected in series so that they practically form one coil. The primary line wires are connected to the terminals a, b, and the secondary line wires to c and a. The pressure E_s depends on the number of turns in the coil t'. For example, if t' were one-third the total number of turns between b and a, the voltage E_s would be one-third the line voltage and the current in the secondary would be about three times that taken from the primary lines.

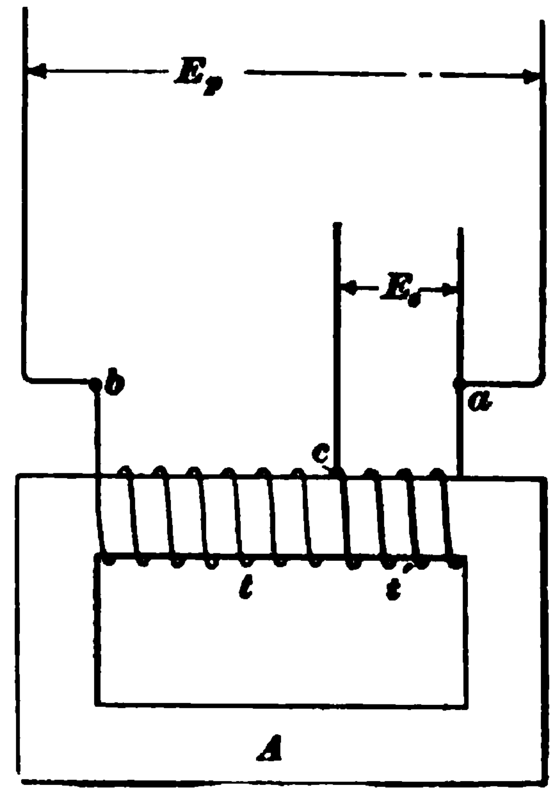


FIG. 13

The autotransformer is not suitable for use in connection with ordinary light and power distribution, because the secondary is in direct electrical connection with the primary, and as the primary pressure is usually very much higher than the secondary, it would be dangerous to have the secondary system of wiring in connection with the primary. On this account autotransformers are only used for special purposes, where there is no great difference between the primary and secondary pressure, or where the use of the device is such that the electrical connection of the primary and secondary does not introduce an element of danger. Autotransformers, for a given capacity, are considerably cheaper to build than ordinary transformers, but their use is comparatively limited for the reason just given.

Autotransformers are sometimes used on low-pressure alternating-current switchboards to supply current to synchronizing lamps or other auxiliary devices. When used in this way, they are sometimes spoken of as *shunt transformers*.

25. Series-Transformers.—Most transformers are run on constant-potential circuits, and their primary coils are connected across the circuit. In some cases, however, **series-transformers** or **current transformers** are used for special purposes. These transformers have their primary connected in series with the circuit, as indicated in Fig. 14, where the coil P is the primary. The secondary is connected to whatever device A the current is to be supplied. As the current through the primary increases, the magnetization in the core will also increase, thus increasing the voltage in the secondary. If the resistance of A is fixed, the secondary current will increase in proportion to the secondary voltage, and hence in proportion to the current in the main circuit. One use of series-transformers has aleady been referred to in connection with the compounding of alternators.

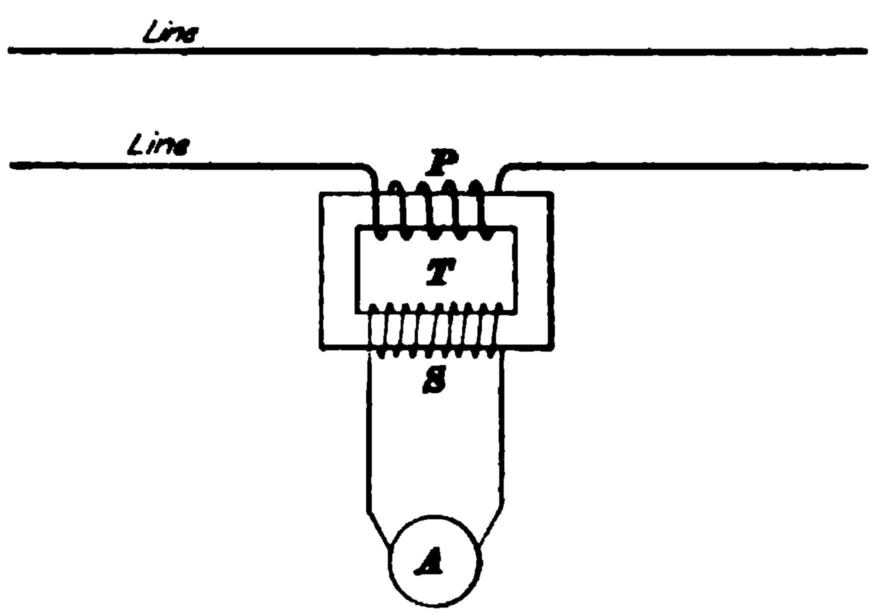


FIG. 14

26. Series-Transformer for Ammeter.—Another very common use of the series-transformer is in connection with alternating-current ammeters. On account of the effects of self-induction, it is not practicable to use shunts with alternating-current ammeters, as is done with direct-current instruments. Shunts can be used with instruments that have practically no inductance, but with instruments of the plunger or dynamometer types the use of a shunt would interfere with the accuracy of the indications. In order to

reduce the current for these ammeters, a series-transformer is connected as shown in Fig. 14. The secondary can be wound so as to supply a comparatively small current to the ammeter A, and as this current is proportional to the main current, the dial of the instrument can be marked to indicate the current in the main circuit. Another, and in some cases a very great, advantage of the series-transformer is that it completely separates the instrument A from the high-pressure lines.

Since the main current is usually quite large, a very small number of turns is sufficient on the primary P; in fact, in some cases, a single turn, or even a fraction of a turn, is enough. In some series-transformers used with ammeters, the secondary coil is wound on a laminated iron core built up of thin annular rings. This coil is simply slipped over the cable or other conductor carrying the main current. The current in the main conductor sets up an alternating flux in the laminated ring, and this sets up the current in the secondary. Fig. 15 shows the secondary for a series-transformer of this type made by the Wagner Company. The iron ring with its winding is mounted on a fiber spool, and the main cable or other conductor carrying the current is passed through the hole in the center. The small flexible leads are connected to the ammeter. When series-transformers are used on very high-pressure circuits, they are generally mounted in cases in the same way as ordinary transformers, and immersed in oil.

Fig. 15

27. Potential Transformers.—It is not usual to connect voltmeters of the ordinary type directly across the

line on alternating-current boards, because the pressure is so great that a voltmeter would require an exceedingly high resistance to permit its being so connected. Of course if the pressure were low, they could be connected in the ordinary way. In case the pressure is high, a small **potential transformer** is used to step-down the voltage. Fig. 16 shows a transformer of this kind. It is generally mounted on the back of the switchboard; its primary coil is connected to the line and its secondary to the voltmeter, as shown in Fig 17. It is bad practice to run switchboard lamps from the potential transformer, because, as a rule, the transformer does not have sufficient capacity for this purpose, and, besides, it is liable to interfere seriously with the accuracy of the voltmeter readings. The voltmeters are usually graduated to read the secondary voltage, as this is what is generally required. In some cases, however they are graduated to indicate the primary voltage.

FIG. 16

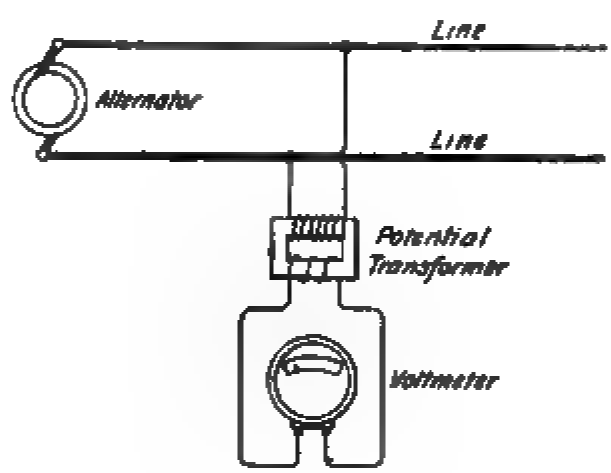


FIG. 17

ALTERNATING-CURRENT MOTORS

28. Motors designed for use in connection with alternating currents may be divided into two classes: (1) *Synchronous motors;* (2) *induction motors.*

Both kinds are in common use, and by far the larger part of all the motors operated in connection with alternating current belong to one of these classes. There are a few other motors that are used to some extent, but their number is insignificant compared with those of these two classes.

SYNCHRONOUS MOTORS

29. Synchronous motors are made to operate either on single-phase or polyphase systems, and are so-called because they always run in synchronism with, or at the same frequency as, the alternator driving them. In construction they are almost identical with the corresponding alternator, and always consist of the two essential parts, field and armature, either of which may revolve. The field of such motors must be excited from a separate continuous-current machine in the same way as an alternator. The fields of synchronous motors are, however, seldom if ever compound-wound, and hence are provided simply with collector rings, no rectifier being required; otherwise, the whole construction of the motor is about the same as that of the alternator.

30. If a single-phase alternator be connected to another similar machine, the latter will not start up and run as a motor, because the current is rapidly reversing in its armature, thus tending to make it turn first in one direction and then in the other. The consequence is that the armature does not get started from rest. If, however, the second machine be first run up to a speed such that the frequency of its alternations is the same as that of the alternator, and

then connected in circuit, the impulses of current will tend to keep it rotating, and the machine will continue running as a motor. The motor must be run up to synchronism by

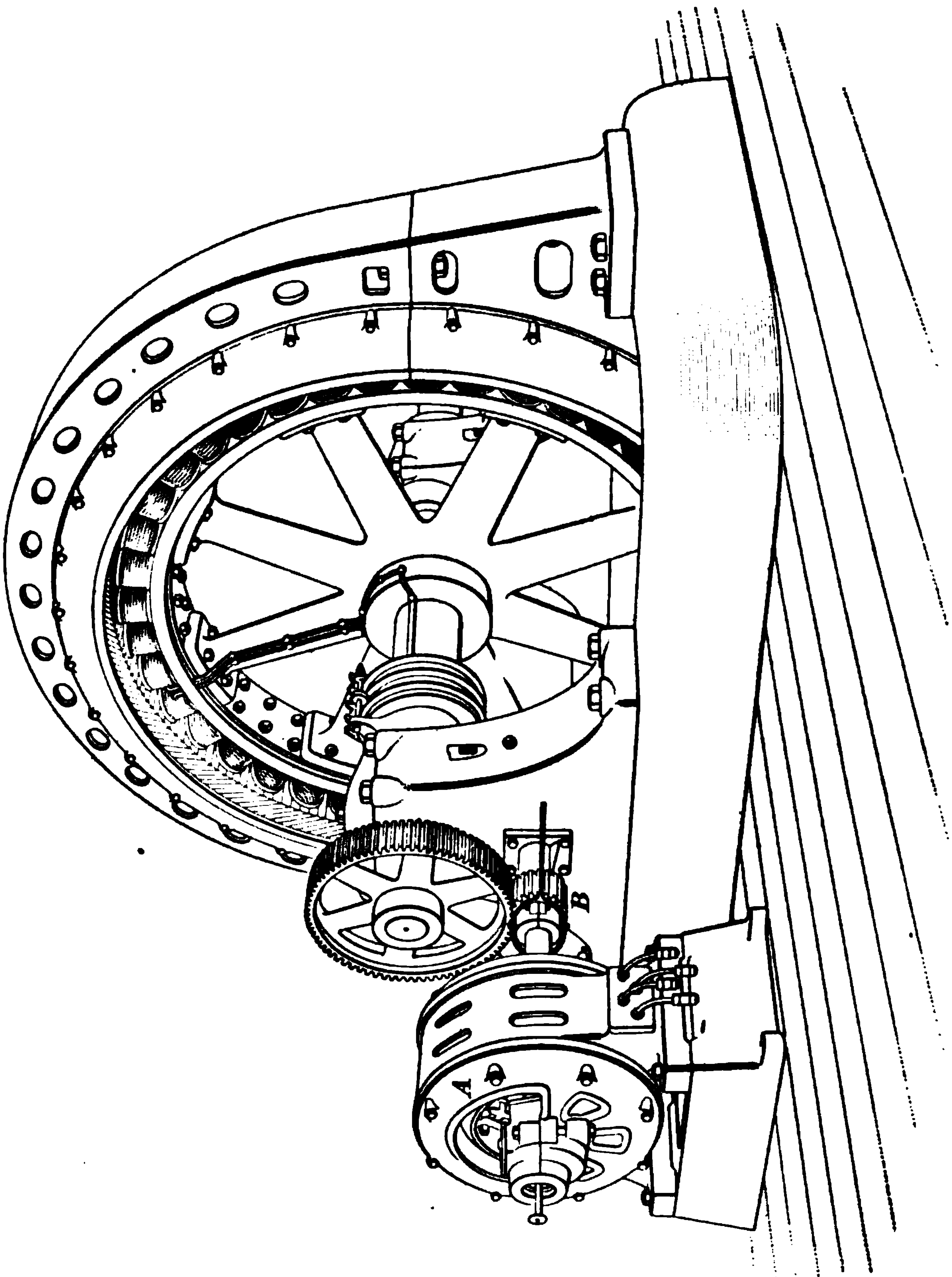


FIG. 18

means of some outside source of power, and the fact that single-phase synchronous motors will not start of their own

accord is a serious drawback to their use; in fact single-phase synchronous motors are now seldom installed. On the other hand, polyphase synchronous motors will start from rest and run up to synchronism when their armature windings are supplied with current, although in doing so they take a large current from the line, and if the motor is a large one, it is better to bring it up to speed by means of some outside source of power, such as an auxiliary motor. When current is supplied to the armature of a polyphase synchronous motor, magnetism is set up in the pole pieces by the armature currents, and on account of hysteresis this magnetism lags behind the current. The consequence is that the magnetism set up by the windings of one phase is reacted on by the current in the following phase, thus producing a torque on the armature and causing the motor to start up. If the pole pieces are not laminated, the volume of eddy currents set up in them may be considerable, and these will also aid in producing a turning moment on the armature; after the machine has come up to synchronism, its fields are excited by an exciter in the same way as an alternator. As stated above, this method of starting by simply connecting the armature to the line results in a large starting current, and is objectionable because of its disturbing effects on other parts of the system. For this reason, large motors are frequently started by means of a small induction motor that brings the large machine up to speed without taking a large line current. After the large motor has been brought up to synchronism, the starting motor is disconnected by means of a clutch, and is then shut down. Fig. 18 shows a General Electric, 1,000-horsepower, two-phase, synchronous motor of the revolving-field type. It will be noted that the construction of the motor is the same as that of a revolving-field alternator. The large motor is brought up to speed by the small induction motor *A*, and after synchronism has been attained, the clutch *B* is thrown out and *A* is shut down.

31. Synchronous motors behave differently in some respects from direct-current machines. If the field of a

direct-current motor be weakened, the motor will speed up. If the field strength of a synchronous motor be changed, the speed cannot change, because the motor must keep in step with the alternator. Such a motor adjusts itself to changes of load and field strength by the changing of the phase difference between the current and E. M. F. Imagine a synchronous motor which, we will suppose, runs perfectly free when not under load. If such a machine were run up to synchronism, and its field adjusted so that the counter E. M. F. of the motor were equal and opposite to that of the dynamo, no current would flow in the circuit when the two were connected. At any instant the E. M. F. causing current to flow is the difference between the instantaneous E. M. F. of the alternator and the counter E. M. F. of the motor. If the motor be loaded, its armature will lag a small fraction of a revolution behind that of the alternator, and the motor E. M. F. will no longer be in opposition to that of the alternator; consequently, there will flow a current sufficiently large to enable the motor to carry its load. The greater the load applied, the larger will be the current that is thus allowed to flow. It must be borne in mind that this phase difference is caused by a small relative lagging of one armature behind the other, not by a difference in speed. For example, the change of phase from full load to no load might not be more than 25°, and this would mean an angular displacement on the machine of a little more than one-eighth of the pole pitch If the machine be loaded too heavily, the slipping back of the motor armature will become sufficiently great to throw the motor out of synchronism, and it will come to a standstill.

32. The action of a synchronous motor may be represented as shown in Fig. 19. A represents the E. M. F. supplied to the motor. If the motor is running in synchronism, and if its voltage were almost equal and opposite to that of the alternator, its pressure would be represented by the dotted line B' lagging 180° behind A. Under such

circumstances very little current would flow, and the motor would exert but a very small torque. When the motor is loaded, the armature slips back a small fraction of a revolution, thus making the counter E. M. F. *B* of the motor lag by an angle α greater than 180°. The E. M. F. that will now be effective in forcing current through the circuit is the resultant of *A* and *B*, and is represented by *E*. The current that will flow may be represented by the line *I* lagging behind the E. M. F. by the angle ϕ that depends on the inductance and resistance of the motor circuit. It is easily seen that if α increases, the effective E. M. F. *E* also increases, and thus increases *I* to an extent sufficient to enable the armature to carry its load. The value of the E. M. F. *B* of the motor can be changed by changing the field excitation of the motor, while the speed is fixed by the speed of the alternator.

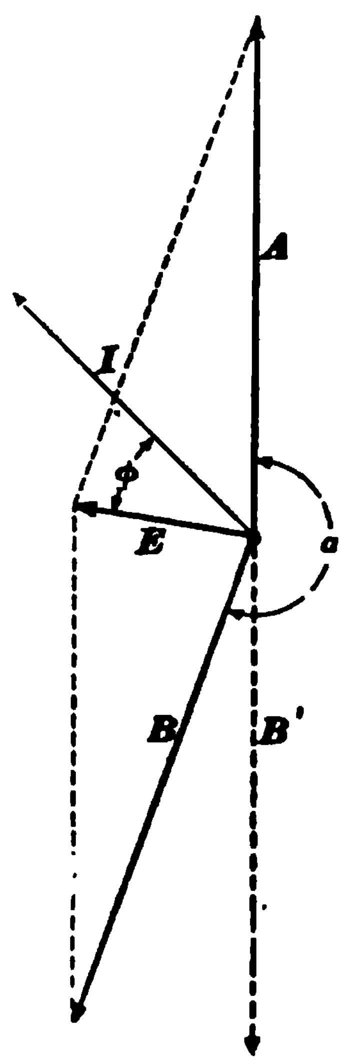


FIG. 19

By adjusting the field excitation of the motor, the current taken by it may be brought almost exactly into phase with the E. M. F. of the line, no matter what the load may be. In other words, a synchronous motor may be adjusted so as to run with a power factor of unity, and this is a considerable advantage, especially where large motors are used. Further, if the field excitation is increased beyond that required to produce a power factor of unity, the current can, with an unloaded or lightly loaded motor, be made to lead the E. M. F. The motor under such conditions acts like a condenser of large capacity, and can, therefore, compensate for self-induction on the system, and improve the power factor of the system as a whole. Synchronous motors have been used to some extent in this way as compensators for self-induction, thus offsetting the bad effects of lagging currents and low-power factor.

33. Synchronous motors are used mostly for work where the motor is not started and stopped frequently, and where

it is not started under load. They are used mostly in the larger sizes. For ordinary work, involving frequent starting and stopping under load, induction motors are preferable.

34. Speed and Direction of Rotation.—The speed at which a synchronous motor will run when connected to an alternator of frequency n is $s = \frac{2n}{p}$, where s is the speed in revolutions per second, and p the number of poles on the motor. For example, if a ten-pole motor were run from a 25-cycle alternator, the speed of the motor would be $s = \frac{2 \times 25}{10} = 5$ revolutions per second, or 300 revolutions per minute. It follows, then, that if the motor had the same number of poles as the alternator, it would run at exactly the same speed, and any variation in the speed of the alternator would be accompanied by a corresponding change in the speed of the motor. A synchronous motor will run in either direction, depending on the direction it is revolved when started up by its auxiliary motor. If, however, it is started by simply allowing current to flow through the armature, its direction of rotation will depend on the way in which the armature terminals are connected to the line. Interchanging any two of the leads of a three-phase motor will reverse the direction of rotation, while interchanging the two wires of either phase of a two-phase motor will accomplish the same result.

INDUCTION MOTORS

35. In a great many cases it is necessary to have an alternating-current motor that will not only start up of its own accord, but one that will start with a strong torque. This is a necessity in all cases where the motor must start up under load. It is also necessary that the motor be such that it may be started and stopped frequently, and in general be used in the same way as a direct-current motor. These requirements are fulfilled by *induction motors.*

36. Induction motors are usually made for operation on two-phase or three-phase circuits, although they are sometimes operated on single-phase circuits, as explained later. They always consist of two essential parts, namely, the *primary*, or field, to which the line is connected, and the *secondary*, or armature, in which currents are induced by the action of the primary. Either of these parts may be the revolving member, but we will suppose that the field is stationary and the armature revolving, as this is the usual arrangement. In a synchronous motor or direct-current motor, the current is led into the armature from the line, and these currents, reacting on a fixed field provided by the stationary field magnet, produce the motion. In the induction motor, however, two or more currents differing in phase are led into the primary, thus producing a magnetic field that is constantly changing and which induces currents in the coils of the armature in the same way that currents are induced in the secondary coils of transformers. These induced currents react on the field and produce the motion of the armature. It is on account of this action that these machines are called induction motors.

37. In order to understand the action of an induction motor, it will help matters to compare it briefly with the action of an ordinary direct-current motor. Suppose we have a direct-current armature surrounded by a four-pole field. If the field is excited and current sent into the armature through the brushes in the ordinary way, the armature will revolve, and the greater the load applied at the pulley, the more current will it take to drive the armature. Suppose that instead of driving the armature in this way, we remove the brushes and press a copper ring over the commutator, so as to connect all the bars together. This will connect all the ends of the armature coils together, making them form a number of closed circuits. Also, suppose that we revolve the field around the armature instead of having it stand still, as is usually the case, and that the armature be held from turning. The lines of force

from the field will cut across the armature conductors and set up E. M. F.'s in them. Since the coils are all short-circuited by the ring on the commutator, heavy currents are set up in them, and these currents reacting on the field produce a powerful dragging action on the armature. If, therefore, the armature is released, it will be dragged around after the field. If the armature revolved at exactly the same speed as the field, the conductors would move around just as fast as the lines of force, and hence they would not be cut by the lines of force, and no current or turning torque would be the result. It follows, then, that the armature must always revolve a little slower than the field, in order that any drag may be exerted. It should be noticed that in this arrangement no current is led into the armature from outside; it is induced in the armature by the revolving field.

The field in this case is supposed to be excited by continuous current and revolved by mechanical means, but by using a two- or three-phase alternating current, we can make the magnetism sweep around the armature without actually revolving the field frame itself. In other words, we can set up magnetic poles that will be continually shifting around the armature without actually revolving the field structure.

38. Revolving Field.—The way in which two-phase currents can be made to set up a rotating magnetic field will be understood by referring to Fig. 20. This represents a simple form of field where the groups of conductors *1*, *2*, etc. are laid against the inner surface of the laminated iron ring *A*. In an actual machine, these conductors would be laid in slots uniformly distributed, as shown in Fig. 21. This represents the stationary part of a Westinghouse two-phase induction motor, the coils *a*, *a* being arranged around the inner circumference and making a winding very similar, so far as the arrangement of coils is concerned, to that used on direct-current armatures. These coils are connected up in the same way as those for a polyphase

alternator armature, and except for motors operating on high pressure, the windings are distributed uniformly instead of being bunched together into a few heavy coils.

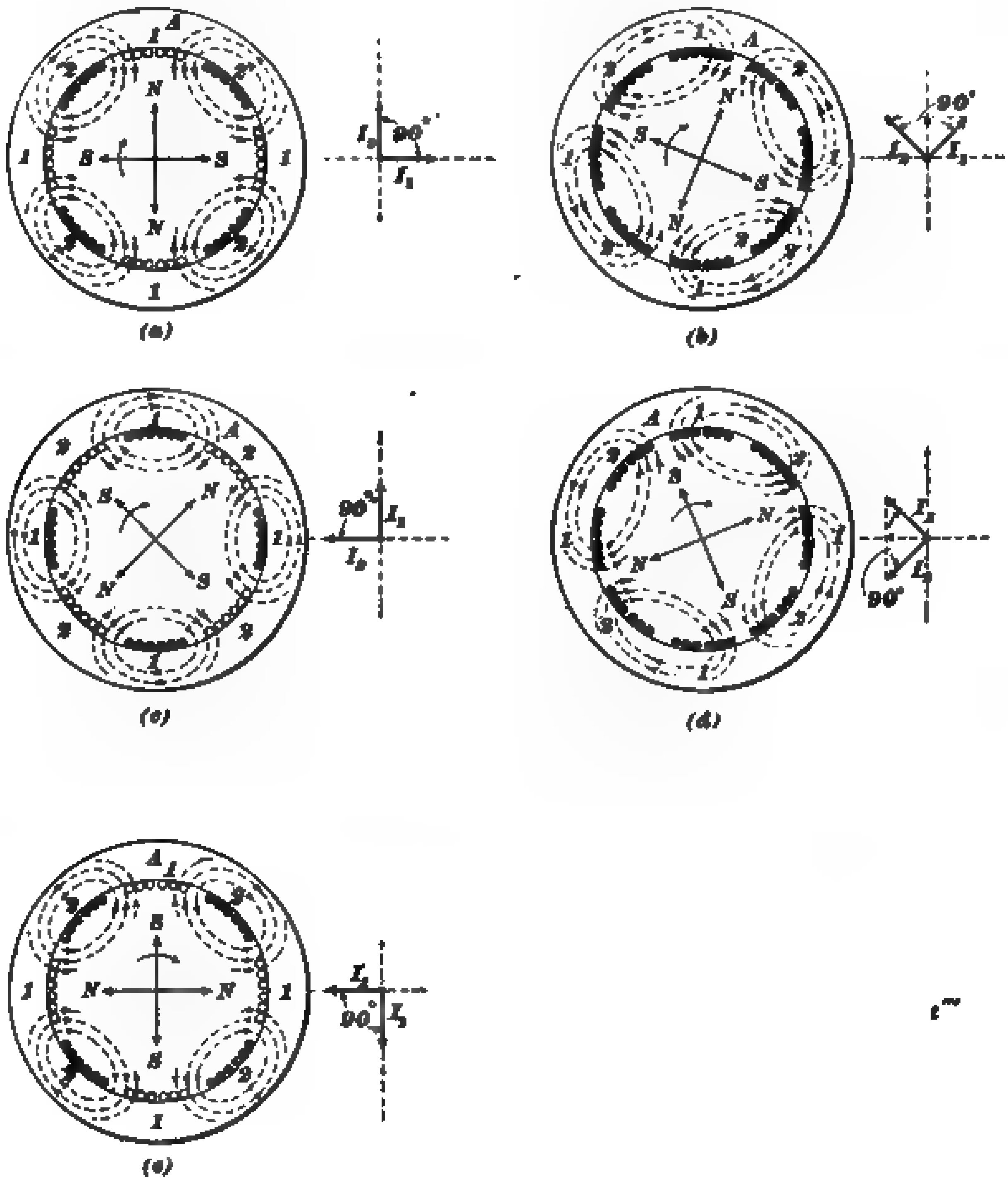


FIG. 20

In Fig. 20 we have taken a four-pole winding with only four groups of conductors for each phase. The conductors belonging to the two phases are marked *1* and *2*, and the

different bands are separated by a small space so as to make the diagrams more easily understood. There are two flat coils for each phase, and these two coils are connected

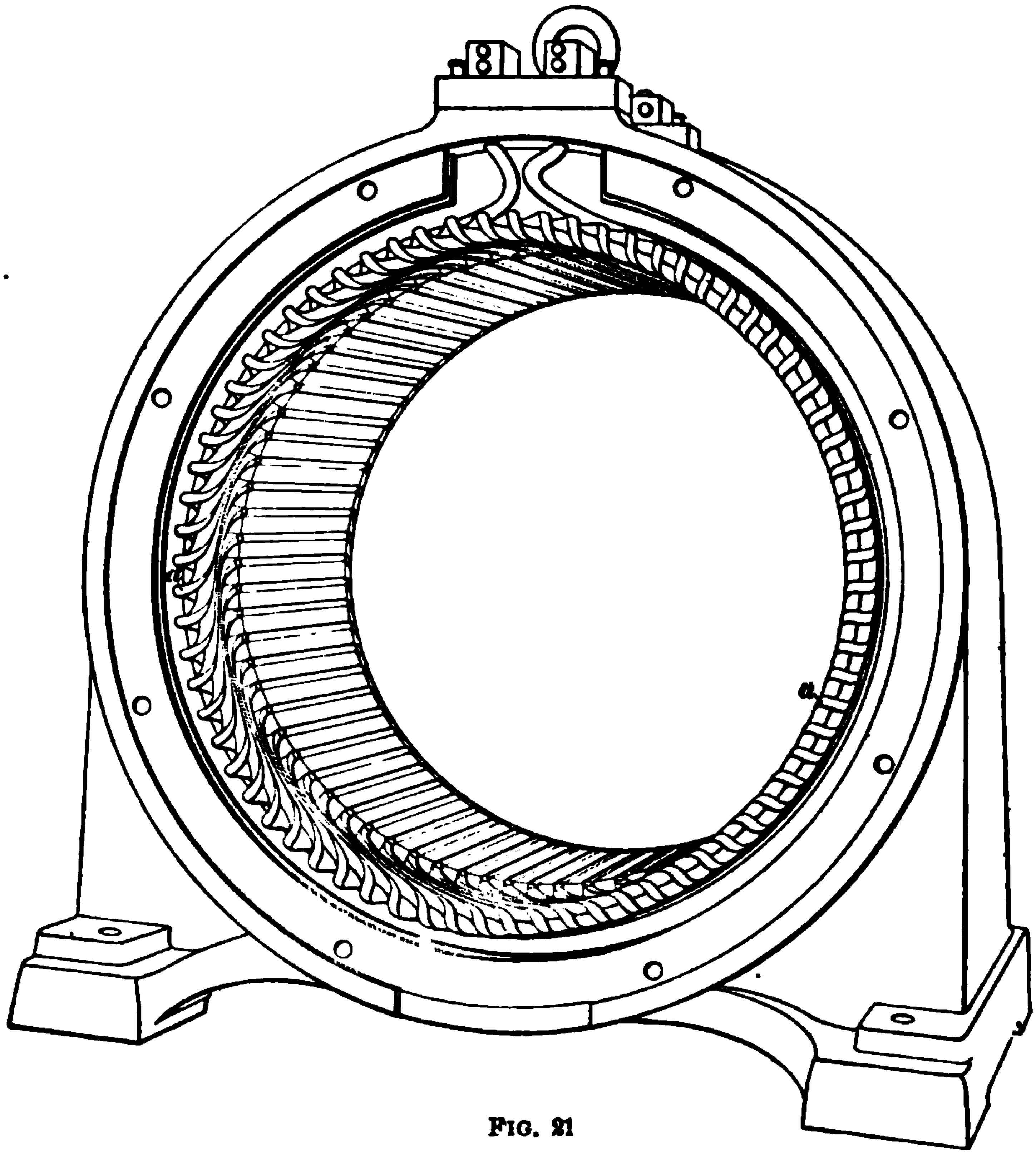


FIG. 21

in series, so that the currents in those conductors that are, in this case, diametrically opposite flow in the same direction. Each coil consists of six turns. Fig. 20 (*f*) shows the ring with two of the coils in place, *t*, *t'* being the terminals of coil *2 2* and *t''*, *t'''* those of coil *1 1*. The other groups of conductors *2 2* and *1 1*, shown unconnected so as not to confuse the figure, are connected up to form two coils similar to those drawn in; the coils marked *2 2* are connected in series as described above, and the terminals

connected to one phase of the two-phase circuit. The other two coils *1 1* are also connected in series and attached to the other phase. Let us now examine the nature of the magnetism set up when this field ring with its coils is provided with two currents I_1 and I_2 differing in phase by 90°.

39. In Fig. 20, the small arrows I_1 and I_2 represent the maximum values of the current in the coils and their projection on the vertical dotted line gives the value of the current at any particular instant. In (*a*) the projection of I_1 is zero, while I_2 is at its maximum; hence, at this instant the current in conductors *2 2* is at its maximum, and there is no current in conductors *1*. From the way in which the coils *2 2* are connected current will flow up and down alternately in the groups of conductors marked *2*, those in which the current flows up through the plane of the paper being marked with a dot, and those with a down-flowing current filled in black. Conductors *1 1* are left blank because at this instant no current flows in them. By remembering the rule governing the direction of current in a wire and the direction of the lines of force set up around it, it can easily be seen that the magnetism set up around the bands of conductors carrying the current will be as shown by the dotted lines. Where these lines leave the face of the ring, as indicated by the arrowheads, a north pole is formed, and where they enter the ring a south pole is formed, the direction of the lines and the current being related in the same way as the direction of turning and movement (downwards or upwards) of a right-handed screw. It is easily seen from (*a*) that four equally spaced poles are formed around the ring, the centers of these poles being indicated by the arrowheads in the center of the figure and also by the letters *N S*.

In (*b*) the condition of affairs, $\frac{1}{8}$ cycle later, is indicated. Here the instantaneous values of I_1 and I_2 are equal and in the same direction, as indicated by their projection on the vertical line. Also, the current in conductors *2* is still in the same direction as in (*a*). The magnetism set up around

the conductors will now be as indicated, and the four poles have shifted around $\frac{1}{16}$ revolution. At the instant shown in (*c*) I_2 has become zero, and I_1 has reached its maximum value. The poles have shifted another $\frac{1}{16}$ revolution in the direction indicated by the arrow. In (*d*) we have the condition of affairs $\frac{1}{8}$ cycle later, when I_1 and I_2 are equal but opposite in direction; I_1 has the same direction as in (*b*), but I_2 is in the opposite direction. The four poles, therefore, occupy the position shown, thus shifting around $\frac{1}{16}$ revolution. One-eighth of a cycle later, I_1 is zero and I_2 at its maximum in the opposite direction, as shown in (*e*); this figure is the same as (*a*), except that the currents in conductors *2 2* are reversed and the poles shift forwards to the position indicated. During the time represented by these figures, the current has passed through $\frac{1}{2}$ cycle, the poles have made $\frac{1}{4}$ revolution around the ring, and as the currents in the two phases continue to change, the magnetism sweeps around, although both the coils and core remain fixed. In the case shown, the field makes $\frac{1}{2}$ revolution for every complete cycle of the current. If a six-pole winding were used, the field would make but $\frac{1}{3}$ revolution for each complete cycle, or in general

$$s = \frac{2n}{p}$$

where s = speed of revolving field in revolutions per second;
p = number of poles;
n = frequency in cycles per second.

40. Armatures for Induction Motors. — Referring again to the direct-current machine, we can replace the mechanically revolved field magnet by a revolving field produced by means of polyphase currents, and if the armature with the short-circuited commutator be placed within such a field it will be dragged around as previously explained. It would, of course, be a needless expense to provide a short-circuited commutator, so that this type of armature would never be used. Fig. 22 shows a very common type of

induction-motor armature intended for use in connection with the field shown in Fig. 21, and its construction is exceedingly simple. The laminated core is provided with a number of slots around its periphery, in each of which an

FIG. 22

insulated copper bar *b* is placed. At each end of the armature is a heavy copper ring *r*, to which the projecting ends of the bars are bolted, thus connecting all the bars together and making them form a number of closed circuits. This arrangement is called a **squirrel-cage armature.** When an armature of this kind is placed in a revolving field, the rotating magnetism sets up E. M. F.'s in the armature conductors, thus causing currents to flow through the closed circuits and exerting a torque on the armature. The iron core of the armature completes the magnetic circuit of the field, so that the magnetism instead of passing through the air, as shown in Fig. 20, passes through the iron of the armature core, thus making the magnetic circuit consist wholly of iron with the exception of the small air gap between armature and field.

41. Slip.—If the armature were held from turning in a revolving field, the coils on the armature would act like the secondary of an ordinary transformer, and heavy currents would be set up in them. However, as the armature comes up to speed, the relative motion between the revolving field and armature becomes less, and the induced E. M. F.'s and currents become smaller, because the secondary turns do not cut as many lines of force as before. If the armature were running exactly in synchronism with the field, there would be no cutting of lines whatever, no currents would be induced, and the motor would exert no torque. Therefore, in order to have any induced currents, there must be a difference in speed between the armature and the revolving field, and the greater the current and consequent torque or effort, the greater must be this difference. When the load is very light, the motor runs very nearly in synchronism, but the speed drops off as the load is increased. This difference between the speed of the armature and that of the field for any given load is called the **slip.** The slip in well-designed motors does not need to be very great, because the armatures are made of such low resistance that a small secondary E. M. F. causes the necessary current to flow. In well-designed machines it varies from 2 to 5 per cent. of the synchronous speed, depending on the size. A 20-horsepower motor at full load might drop about 5 per cent. in speed, while a 75-horsepower motor might fall off about $2\frac{1}{2}$ per cent. For example, if an eight-pole motor were supplied with current at a frequency of 60, its field would revolve $\frac{60}{4} = 15$ revolutions per second, or 900 revolutions per minute, and its no-load speed would be very nearly 900. At full load the slip might be 5 per cent., so that the speed would then be 855 revolutions per minute. It is thus seen that as far as speed regulation goes, induction motors are fully equal to direct-current machines. If S' represents the speed of the armature and S the speed of the revolving field in revolutions per second then

$$\text{slip} = S - S', \qquad \textbf{(5)}$$

or expressed as a percentage of the speed that the armature would run at if it were in synchronism with the field,

$$\text{slip (per cent.)} = \frac{(S - S')\,100}{S} \qquad \textbf{(6)}$$

Since the armature revolves very nearly as fast as the rotating magnetic field, the currents in the armature are of correspondingly low frequency. The greater the slip, the greater is the frequency of the currents in the secondary. If the secondary were held from turning, the slip would be 100 per cent., and the frequency of the secondary currents would be the same as that of the primary. If the slip were, say, 5 per cent., and the primary frequency 60 cycles per second, the frequency of the secondary currents would be 3 cycles per second. On account of the fact that induction motors do not run in synchronism with the source of supply, they are often called *asynchronous* motors, to distinguish them from the synchronous type.

42. In speaking of induction motors, the stationary part is often referred to as the **stator,** and the rotating part as the **rotor.** In order to avoid the use of slip rings, the field, or primary, into which the currents are led from the line is usually the stator, while the armature, or secondary, in which the currents are induced is the rotor. The terms primary and secondary are used in reference to the field and armature, because of the similarity between the action of the induction motor and the ordinary transformer.

43. Relation Between Torque and Slip.—If the armature ran in synchronism with the field, the torque would be zero, as explained above, because there would then be no current in the armature. As the slip increases, the torque also increases, and it would increase in direct proportion were it not for the demagnetizing effects of the currents in the armature. The currents in the armature oppose the magnetizing action of those in the field, and as the armature current increases, this opposing action causes part of the magnetism to leak across the space between the primary and

secondary in much the same way as magnetic leakage occurs in an ordinary transformer. The result is that as the slip and the armature currents increase, the demagnetizing action and magnetic leakage also increase, so that while the armature current is large, the flux through the armature becomes smaller and the torque may actually become less instead of greater. For every motor there is a certain slip at which the maximum torque is exerted, and beyond which the reaction of the armature becomes such that the torque decreases with increase of slip. This point depends on the construction of the motor. The torque at starting, i. e., with slip 100 per cent., depends largely on the resistance of the armature. If the armature has a very low resistance, the current in it at starting will be very large, the armature reaction will be large, and the resulting torque small. If, on the other hand, the armature resistance is high, the current will be limited in amount and the starting torque will be high, because the current that flows in the armature will have a strong field to react on. An induction motor with a high armature resistance exerts its maximum torque at a low speed, while one with a low armature resistance exerts its maximum torque at a high speed. It is thus seen that by varying the construction of a motor of given size and output, its performance as regards torque, speed, etc., can be changed considerably.

The curve in Fig. 23 shows the relation between the torque and speed of a typical induction motor. The point *o* represents a slip of 100 per cent., i. e., the motor is at a standstill, and point *a* represents a slip of zero, i. e., synchronous speed. When the motor is running at synchronism, the torque is zero, and as the speed falls off from synchronism the torque rapidly increases until the maximum value *b c* is reached. With further increase in the slip, the torque falls off until at a standstill it has fallen to the value *o d*, which would represent the torque at starting.

44. Induction Generator.—If the motor is to be driven above synchronism, a torque must be applied in the negative

direction, or, in other words, power must be supplied to the motor from an outside source, as indicated by the curve *a e f*. If driven above synchronism in this way, the induction

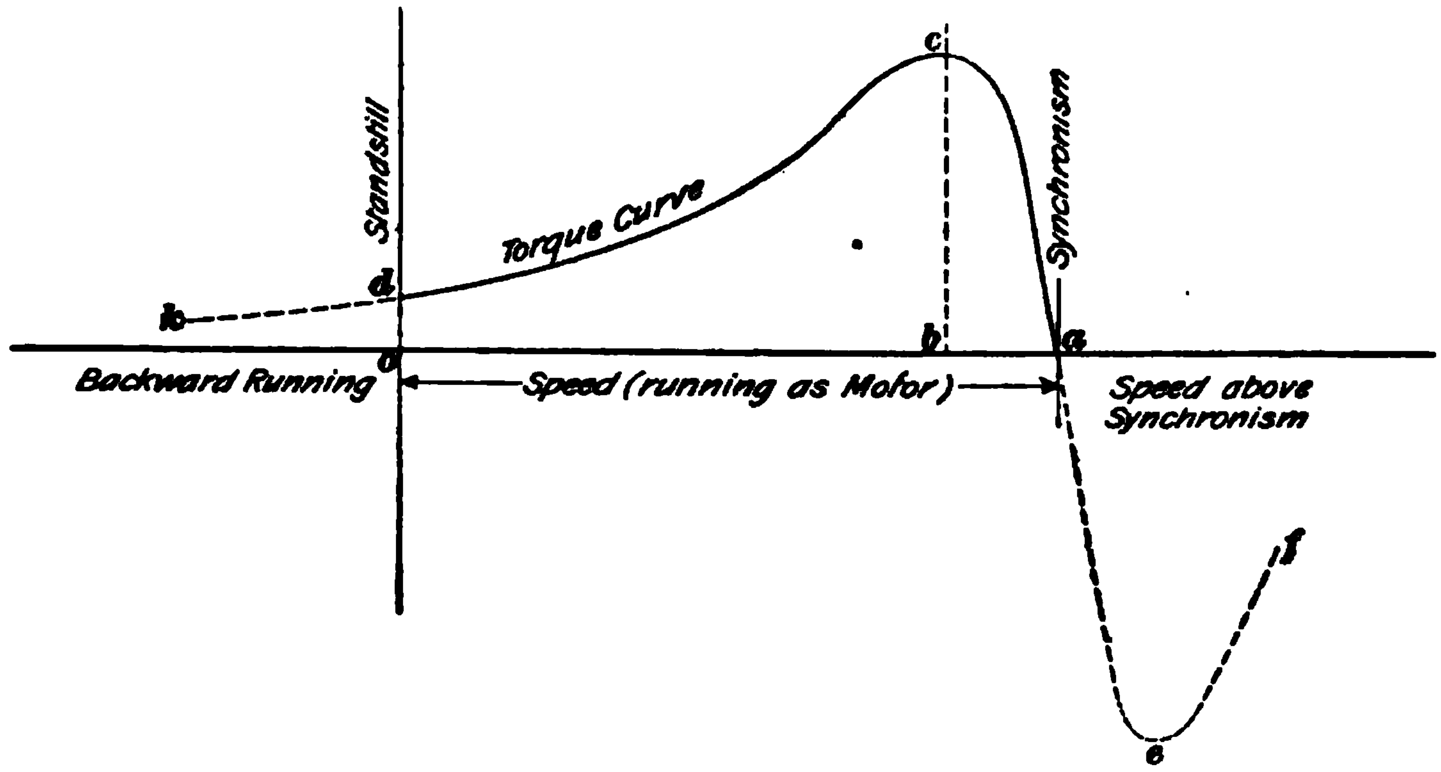


FIG. 23

motor would give back current to the line and would therefore be an **induction generator.** In order that an induction generator may furnish current, it must be connected to an alternator or live circuit that is capable of exciting its field. Induction generators have not been used to any extent in practice, though in a few cases where induction motors have been used for operating electric cars, they have been made to act as generators to return current to the line when the cars descend grades, thus acting as an electric brake and at the same time returning energy to the system. If the motor were driven backwards, as represented by *d k*, then since the torque is in the same direction as before, the motor would simply act as a brake. The portion of the torque curve that represents the actual conditions under which the motor is run is that lying between *a* and *c*. If the motor is loaded beyond the point represented by *c*, the torque will diminish and the motor will stop.

45. Reversing Direction of Rotation.—In order to reverse the direction of rotation of an induction motor, it is necessary to reverse the rotation of the revolving magnetism set up by the field windings. In a two-phase motor

this can be done by reversing the current in either of the phases, i. e., by interchanging the connections of one of the phases with its terminals on the motor. A three-phase motor can be reversed by interchanging the connections of any two of the line wires with the motor terminals.

46. Speed Regulation of Induction Motors.—As already stated, the induction motor tends to run nearly in synchronism with the alternator that supplies it with current. Its speed can never quite reach synchronism, because it always takes some power to make up for the friction losses, etc., even if the motor is unloaded. It is also evident that the speed cannot rise above that of synchronism, and that with the exception of the slight variations in speed, due to the changes in load and corresponding change in the slip, the speed of the motor remains practically constant as long as the speed of the alternator and voltage on the line remain constant. Generally speaking, the induction motor is not as well adapted for variable speed as the direct-current motor, although its speed can be varied through a considerable range. Speed regulation of induction motors is usually accomplished by providing the armature with a regular three-phase Y-connected winding and connecting a variable resistance in series with each branch.

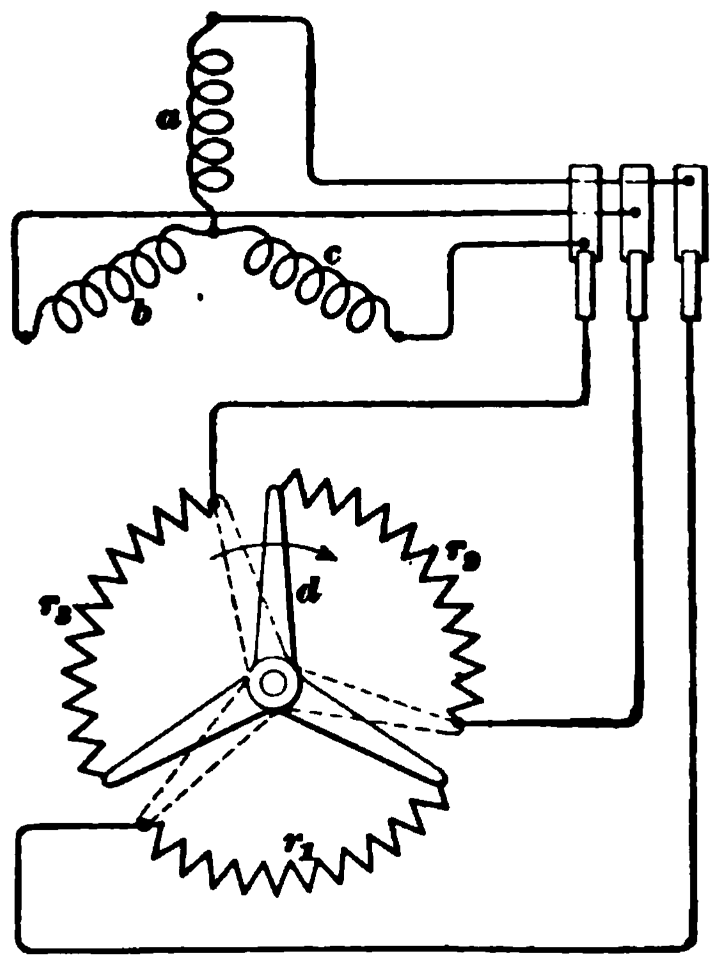


FIG. 24

Fig. 24 shows the method referred to. The bar winding on the armature is arranged in three phases *a*, *b*, *c*, Y-connected, instead of the simple squirrel-cage arrangement. The three terminals of the winding are connected to collector rings mounted on the shaft, and from them the armature

current flows through the resistances r_1, r_2, r_3. When the resistance arm d is in the position shown, all the resistance is in circuit, but when the arm is moved around to the dotted position, as indicated by the arrow, the three ends of the winding are connected together directly through d, thus short-circuiting them. When there is a high resistance in the armature circuit, the slip must be large in order to make enough current flow to provide the requisite torque; consequently, when all the resistance is in, the speed of the motor will be low. Where motors are used for operating cranes or other hoisting machinery, it is necessary to have a variable speed, and this is usually accomplished in the manner just described.

METHODS OF STARTING INDUCTION MOTORS

47. An induction motor may be started by connecting its field directly to the line, but this allows a large rush of current, which disturbs other parts of the system and is, therefore, objectionable. This method of starting is not practicable with any but small motors. In order to obtain a smooth start and thus avoid a rush of current, either of two methods may be adopted. The voltage applied to the primary may be reduced either by inserting a resistance or by the use of an autotransformer. Or a resistance may be inserted in the secondary at starting, and cut out when the motor comes up to speed.

48. Starting Compensator, or Autotransformer.—Where a motor is provided with a squirrel-cage winding, it is generally started by cutting down the voltage applied to the primary. This is usually done by means of an autotransformer inserted between the line and the motor field, the transformer being provided with a double-throw switch, so that it can be cut out when the motor has come up to speed.

Fig. 25 shows a **Stanley starting compensator, autotransformer,** or **autostarter,** as it is variously called. This

starter is intended for a three-phase motor, and is equipped with three autotransformers, one for each phase. The coils and cores of the transformers are contained in the box *M*, for which *E* is the cover. The switch contacts are controlled by the lever *S* and are arranged so that the circuits are always broken under oil contained in the receptacle *D* (which is here shown removed from its normal position). The motor is started by throwing the switch *S* from the off-position to the starting position; these points are plainly marked on the side of the box *M*. After the motor has come up to speed, the switch is thrown over to the running position, thus cutting the autotransformers out of circuit. Fig. 26 shows the connections. Wires *a*, *b*, *c*, Fig. 25, connect to the three-phase supply mains, and *A*, *B*, *C* are the coils of the autotransformers, each of which is provided with a number of taps *1*, *2*, *3*, *4*, Fig. 26. When the switch is thrown to the left, coils *A*, *B*, *C* are connected in circuit with the supply mains. The motor windings are, however, connected only across that portion of each coil that lies between the points *1* and *5*; consequently, the voltage applied to the motor is decreased and the current is correspondingly increased. The voltage applied to the motor at starting can be adjusted by using the taps *1*, *2*, *3*, *4*, so that the starting current can be varied to suit the conditions under which the motor is used. A simple arrangement is provided so

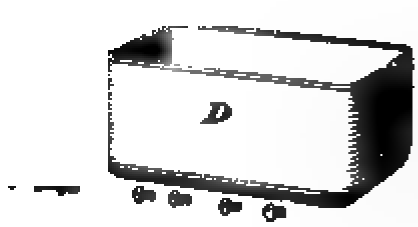


FIG 25

that leads *l*, *l'*, *l''* can be connected to points *1*, *2*, *3*, or *4*, as desired. If connection is made at point *4*, the maximum starting effort is obtained with a correspondingly large current taken from the line. The General Electric Company also uses a similar starting device in connection

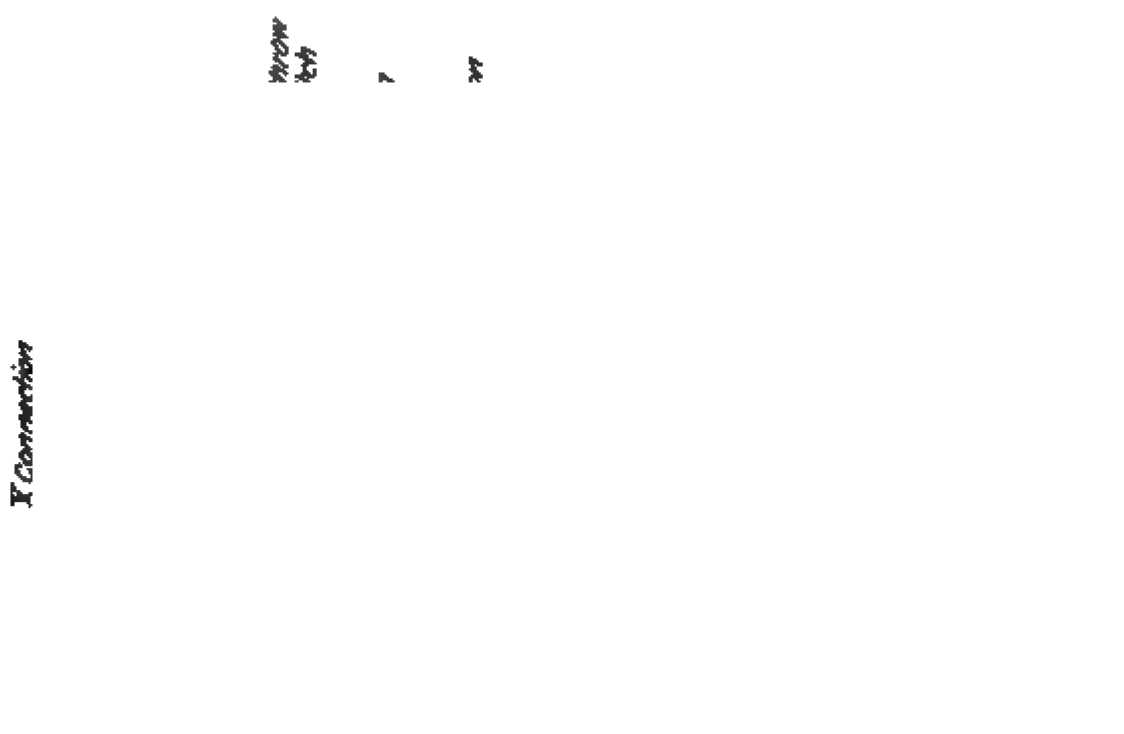
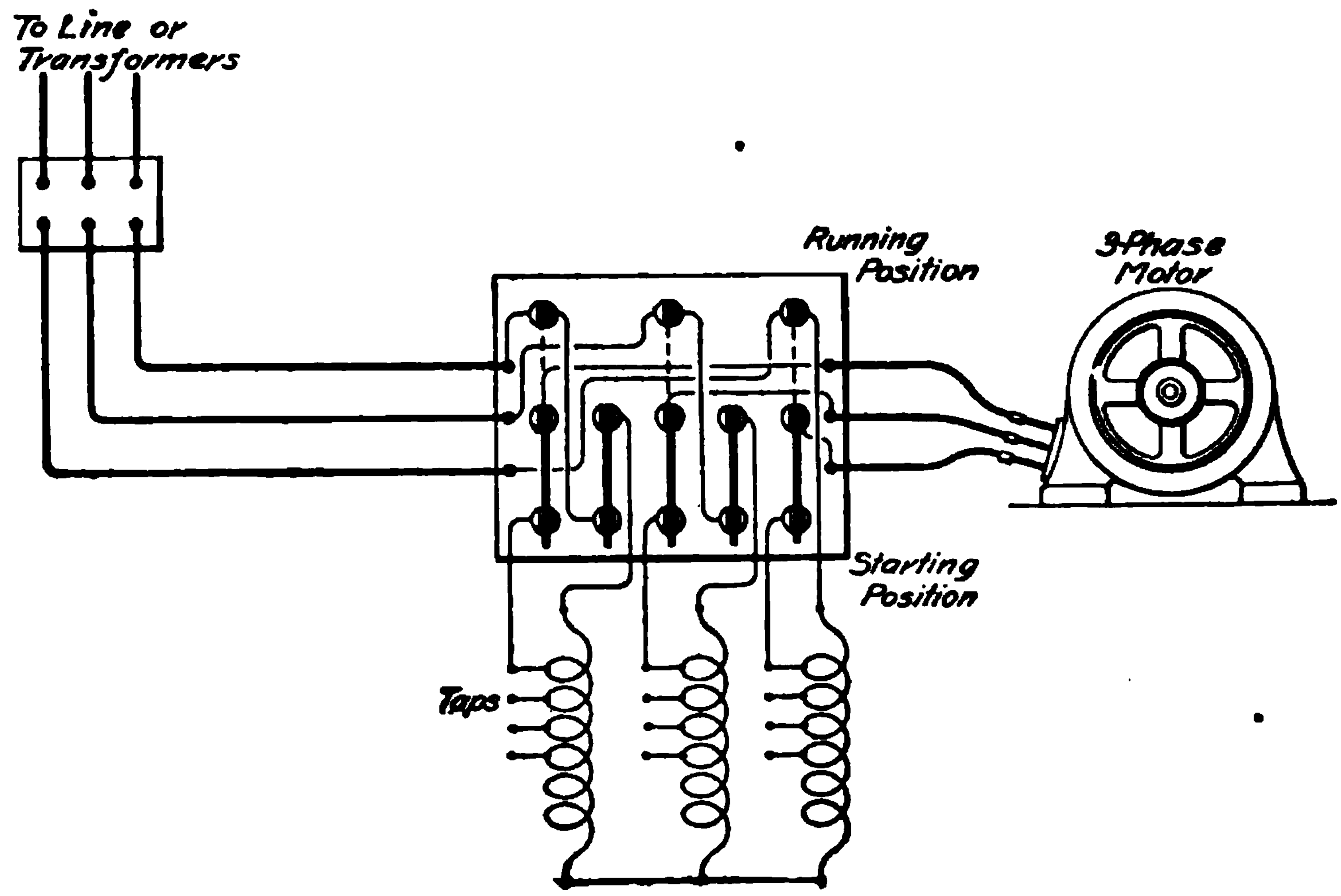


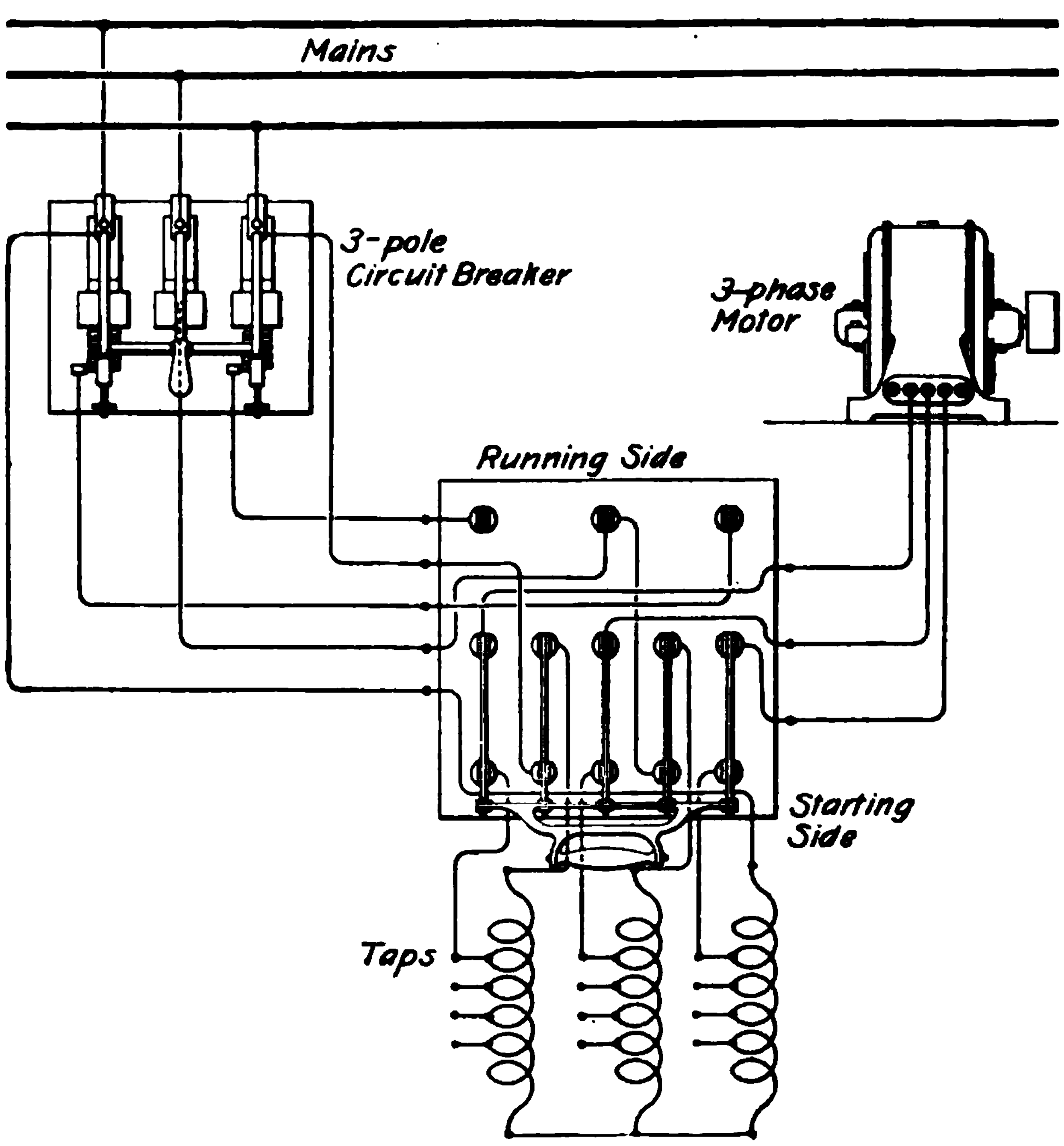
Fig. 26

with their two- and three-phase induction motors. The three-phase starter has three coils, and its principle of operation is the same as that just described. When starting motors with such devices, time should be allowed after the switch is placed in the starting position for the motor to come up to nearly full speed before turning the switch to the running position, otherwise the fuses will be blown. Fig. 27 (*a*) shows the connections of the General Electric three-phase starting compensator.

In Fig. 27 (*a*) a main switch is shown between the starting compensator and the line. This is not always installed, because the compensator itself can be made to answer the purpose of a switch; however, it is better to have a main switch or circuit breaker, so that the compensator can



(a)
FIG. 27



(b)
FIG. 27

be completely cut off from the line if occasion demands. An induction motor if overloaded excessively will stop and will soon overheat unless the current is cut off. In order to protect these motors, either fuses or circuit breakers may be used, though sometimes they are installed without any protective device. The fact that the motor stops if loaded excessively is often depended on to serve as an indication of overload, but this method cannot be recommended, and it is better to have some form of protective device.

The trouble with fuses and circuit breakers, if installed in the usual manner, is that they may open the circuit when the motor is being started, because there is always a large current for a short interval, even if everything is all right. The protective devices thus act when they are not wanted to, and for this reason they are often omitted. In order to overcome this objection, the fuses, see Fig. 26, may be connected so that they will not be in circuit during the starting interval, but will be cut in during the time the motor is in operation. Fig. 27 (*b*) shows a three-phase motor with its starting compensator protected by a triple-pole Cutter circuit breaker (a detailed description of this circuit breaker will be found in a later section). The circuit breaker opens all three lines, but the tripping coils are only in circuit when the compensator switch is in the running position. An overload during the regular operation of the motor will therefore cause the breaker to open the circuit, whereas the large starting current will not.

In some cases a low starting voltage can be obtained without the use of a compensator. For example, the step-down transformers that supply the motor can have taps brought out from the middle point of their windings and connected to a double-throw switch, so that in one position of the switch the motor gets only half the normal voltage, while for the running position of the switch it is connected across the secondaries in the usual manner and gets the full voltage. Another scheme that has been used with two-phase alternators having the two armature windings interconnected, as, for example, in Westinghouse two-phase

machines, is to provide a double-throw switch, so that at starting the motor is connected across the "side phases." Instead of receiving the full-line voltage E, it then has a voltage $\frac{E}{\sqrt{2}}$ applied to it, and after it has come up to speed, the switch is thrown over and the motor receives the full-line voltage E of each phase. This method is used considerably in shops where induction motors are supplied with current directly from the alternator.

49. Starting With Resistance in Armature.—The compensator method of starting has the advantage of being simple and allowing the use of a squirrel-cage armature, which is easy to construct and not liable to get out of order. Also, the starter can be placed in any convenient location.

FIG. 28

thus permitting the motor to be controlled from a distant point. On the other hand, the torque of an induction motor decreases very rapidly when the applied voltage is decreased; it varies as the square of the applied voltage, and if a strong starting torque with a moderate current from the line is desired, it is better to use a resistance in the armature when starting, and apply the full voltage to

the field. Since the starting resistance is only in use for a short time, it may be made of sufficiently small bulk to be mounted on the supporting spider of the armature, thus doing away with the collector rings shown in Fig. 24. Where the resistance is used for speed-regulating purposes, considerable heat is generated in it all the time the motor is running; this heat would be objectionable in the machine, and, besides, a resistance for continuous use would usually be too bulky to mount within the armature.

Fig. 28 shows an armature for a General Electric induction motor in which the resistance is mounted on the spider. The resistance is in three parts *a*, *b*, *c*, one part for each

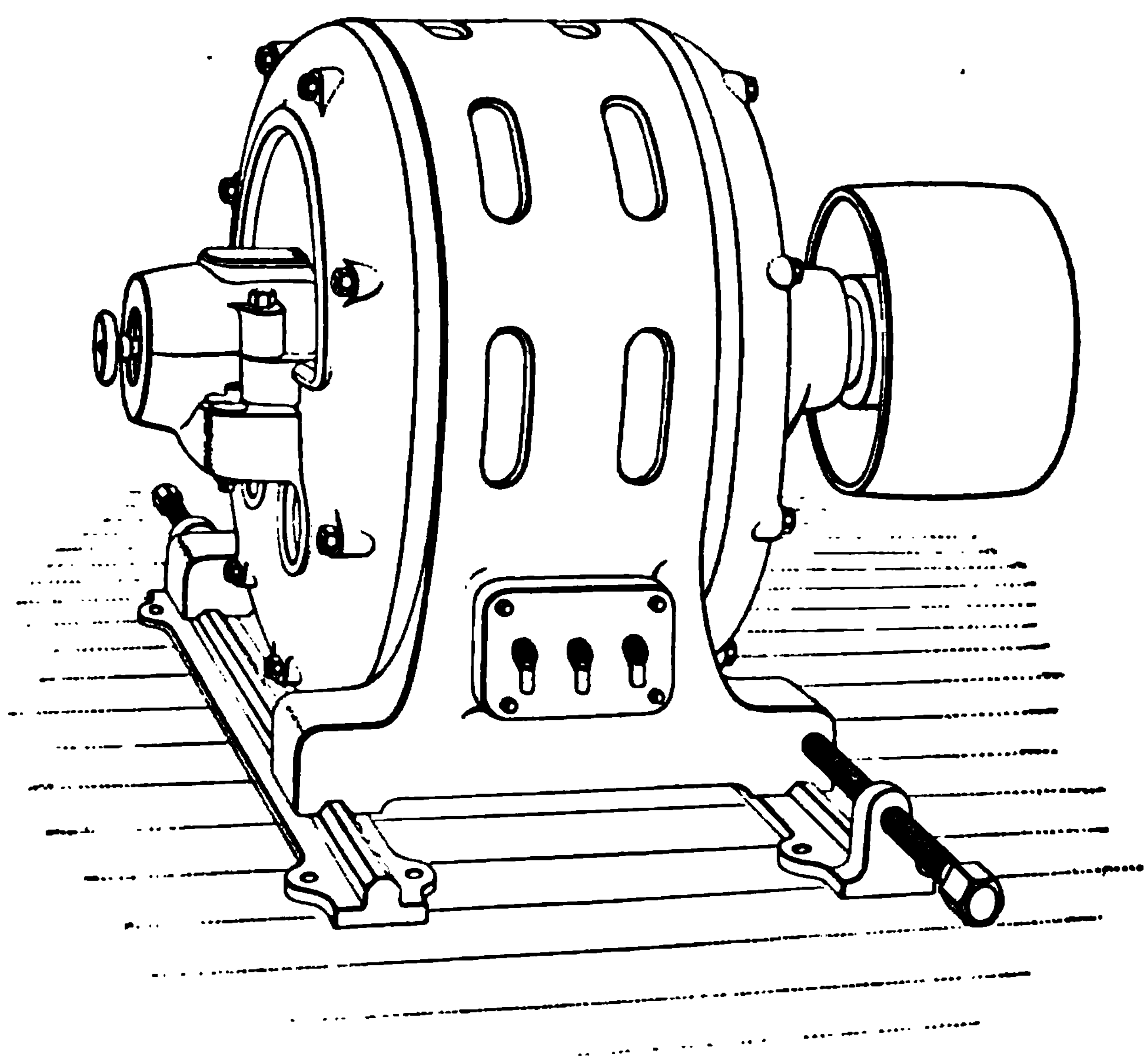


FIG. 29

phase, and is made in the form of cast grids. It is cut out of the armature circuit by means of a sliding switch operated by a loose knob attached to a spindle running through the center of the shaft. The sliding contact that cuts out the resistance is attached to the end of this

spindle, and by pushing in the knob when the motor attains its speed, the resistance is cut out and the three phases of the armature winding directly short-circuited. By adopting this construction, the use of collector rings is avoided, but the construction of the armature as a whole is considerably more complicated than that of the squirrel-cage type.

Fig. 29 shows a General Electric three-phase motor equipped with the style of armature shown in Fig. 28. To start a motor of this kind, all that is necessary is to see that the knob is out as far as it will go, so that all the resistance is in circuit; then throw in the main switch.

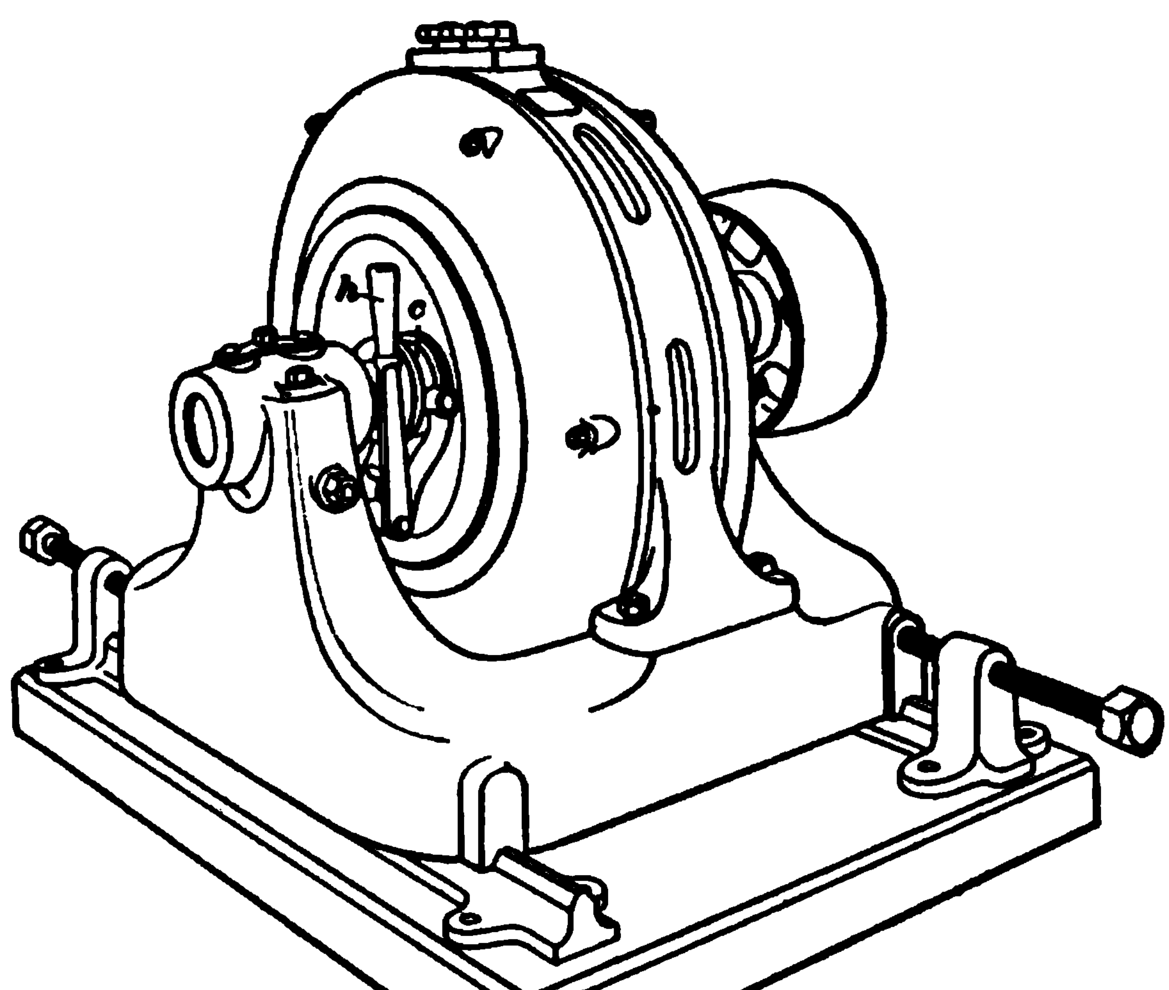


FIG. 30

The motor will start up with a good torque accompanied by a moderate line current, and will come up to speed in about 15 seconds, during which time the knob is pushed in, thus cutting out the resistance.

Fig. 30 shows one of the earlier types of General Electric motor in which the starting resistance is cut out by the sliding collar *c* operated by the lever *h*.

FIELD CONNECTIONS

50. As already pointed out, the **field connections** of a multiphase induction motor are similar to those of a multiphase alternator armature, and what has been said regarding alternator armatures applies to induction motor fields. The field windings of a three-phase motor may be connected either **Y** or Δ, depending on which is best adapted to the voltage and current with which the motor is to operate. If, for example, the field were to be connected to high-potential mains, it would probably have its coils con-

(b)

Fig. 31

nected **Y**. Fig. 31 shows a simple arrangement of coils suitable for a three-phase motor field; the connections between the coils are not shown, as the figure is intended simply to illustrate the grouping of the coils. The stampings *F* are provided with 24 slots, in which are placed 12 coils, *a*, *b*, *c*, etc. The coils belonging to the three different phases are shaded differently, in order to distinguish them from one another. The four coils of each group may be connected in series or parallel, and the three groups then

connected together either Y or Δ. Fig. 31 (*b*) shows how the coils are arranged so that the ends will clear each other. This field winding is designed for an eight-pole revolving field, and the student should compare it with the corresponding alternator winding.

51. The field winding of induction motors usually consists of several groups of conductors per pole per phase, instead of a single group, as shown in Fig. 31 (*a*), and the winding becomes uniformly distributed, as shown in Fig. 21. Sometimes, however, the field is wound to take current at high pressure, and in such cases it is necessary to design the winding so that it will be as free as possible from crossings, and consist of a comparatively small number of coils that can be thoroughly insulated. For motors of this type, a winding similar to that shown in Fig. 31 would be suitable.

52. Power Factor of Induction Motors.—Induction motors always give rise to lagging line currents; that is, the actual watts taken from the line are not equal to the volts × amperes, but this product multiplied by the **power factor of the motor.** The higher the self-induction of the motor and the higher the frequency, the lower

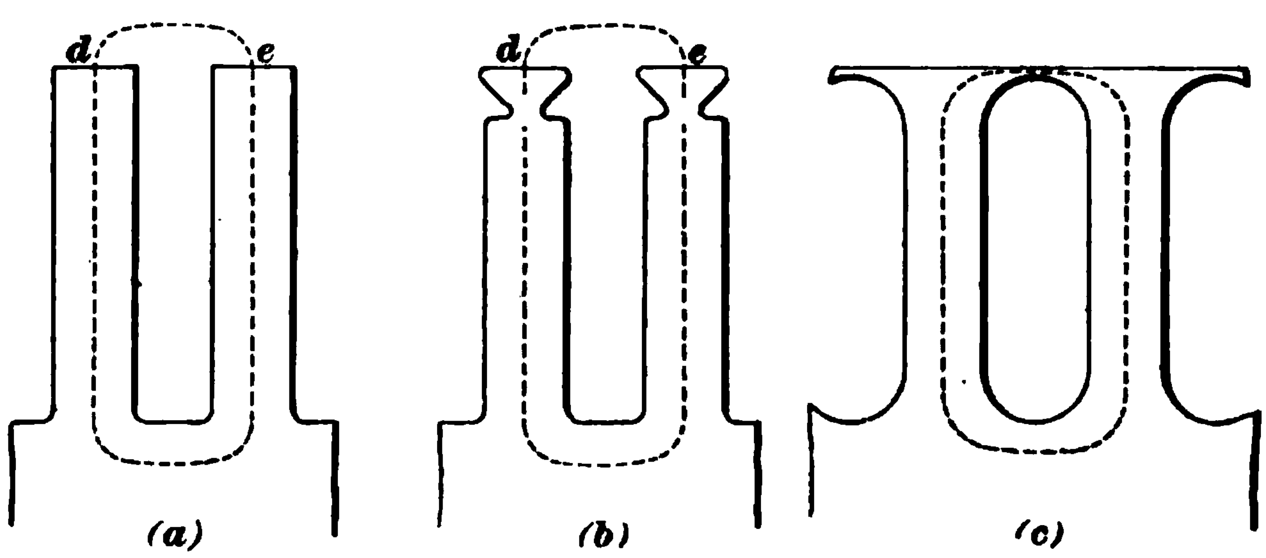


FIG. 32

will be the power factor, other things being equal. Every effort is made to design induction motors so that the power factor will be high. The use of open slots, as at (*a*) and (*b*), Fig. 32, tends to keep down self-induction, because an air gap *d e* is introduced into the path of the magnetic lines that the coil tends to set up around itself. If closed slots are

used, the inductance is greater, because the coils can set up a flux through a complete iron path. The power factor, cos ϕ, of a good motor of medium size operating on 60 cycles should be from .85 to .87 at full load. Motors of large size may have power factors of .9 and over.

53. Induction motors are always constructed with a multipolar field, so as to keep down the speed of rotation. The number of poles employed increases with the output, and the speed is correspondingly decreased. The following table gives the relation between poles, output, and speed for some of the standard sizes of induction motors (60 cycle).

TABLE I

INDUCTION MOTORS

Poles	Horsepower	Speed
4	1	1,800
6	5	1,200
6	10	1,200
8	10	900
8	20	900
10	50	720
12	75	600

54. Characteristic Curves of Induction Motor.—The general performance of an induction motor is best illustrated by means of curves showing the relation between output and speed, power factor, efficiency, slip, etc. Fig. 33 shows curves for a 30-horsepower 60-cycle 110-volt motor, given by Steinmetz. As the load is increased, the speed falls off and at full load, 30 horsepower, it has dropped about 3 per cent. The power factor increases with the load, and at full load it is about 83 per cent. As the load is still further increased, the power factor reaches a maximum of about 85 per cent. The apparent efficiency of the motor is the ratio of the watts output to the apparent watts input, and its value at full load is about 71 per cent. The actual efficiency of the motor is, however, considerably higher than this because the actual

input is less than the apparent, being equal to the apparent watts multiplied by the power factor. The actual efficiency at full load is about 86 per cent. The maximum load that the motor will deliver without stopping is a little over 60 horsepower. This point is indicated by the bending of

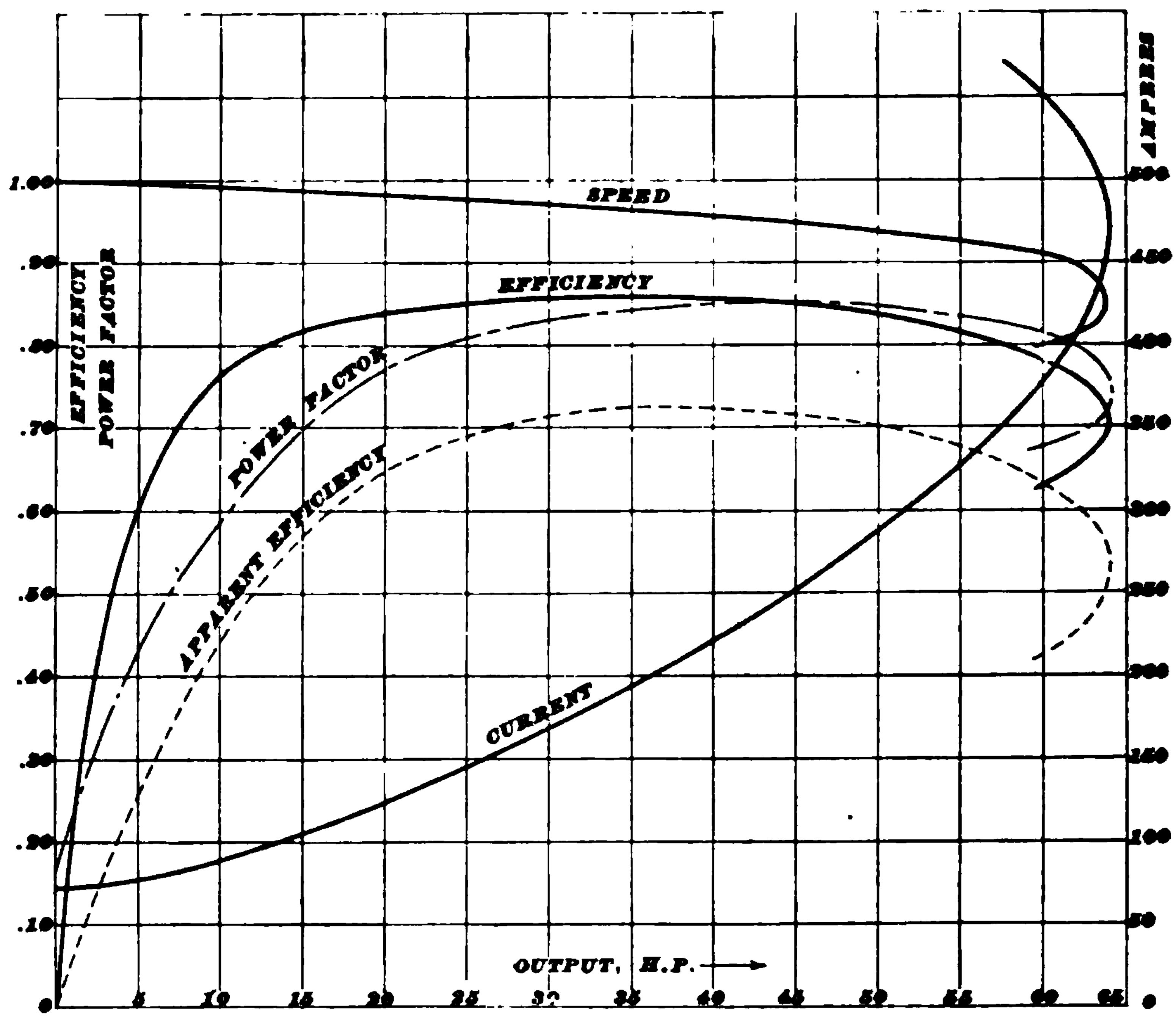


FIG. 33

the curves. Of course, in actual work the motor would not be loaded to anything like this amount on account of the excessive heating that would result.

SINGLE-PHASE INDUCTION MOTORS

55. If a motor constructed on the same lines as an induction motor, but provided with only a single winding on the field instead of two or more sets of windings differing in phase, were connected to single-phase mains, it would not

start up of its own accord. If it were given a start by pulling on the belt, it would gradually come up to speed in whichever direction it was started, provided no load was applied. The motor would exert very little torque, but it would gradually increase in speed until it attained a speed nearly in synchronism with the generator. After the motor has been started, the load may be applied and the motor will behave in the same way as one operated on a polyphase system. A two-phase or three-phase motor will run on one phase after it has been started, though, of course, it will take more current in the single-phase than when all the phases were in use.

When current is first applied to such a motor, it acts as an ordinary transformer, currents being set up in the secondary. The magnetic field is set up by the joint magnetizing action of the primary and secondary currents, as in the case of a transformer, and when the armature is given a start and made to revolve, these induced secondary currents are carried around in space with regard to the primary, so that a similar effect is produced as if the primary were provided with windings displaced in phase. As the armature comes more nearly into synchronism, the combined action of the primary and secondary currents is to produce a rotating field very similar to the true rotating field set up by two or more windings supplied with polyphase current. The objections to a motor of this kind are, of course, that it will not start up of its own accord and that it will not start under load; it is only after the motor has attained its speed that it will carry a load and behave in general like a two- or three-phase induction motor.

56. In order to make a single-phase motor start from rest and give a good starting torque, it is necessary to provide a rotating field at starting. This can be done by using regular two-phase or three-phase windings and supplying these windings with displaced E. M. F.'s obtained by *splitting the phase*, as it is called. Many different methods for phase splitting are in use.

In Fig. 34 the motor is provided with a two-phase winding, and in series with winding A, a non-inductive resistance

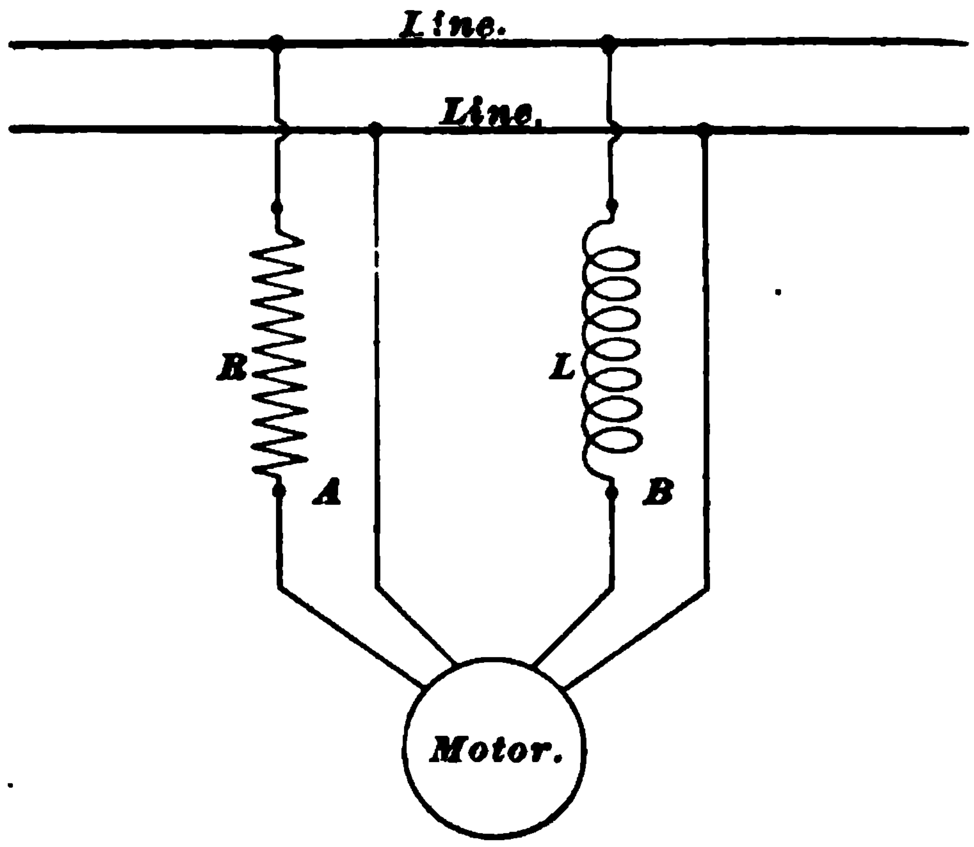


FIG. 34

R is connected. An inductance L is connected in series with B, and the two windings are connected in parallel across the

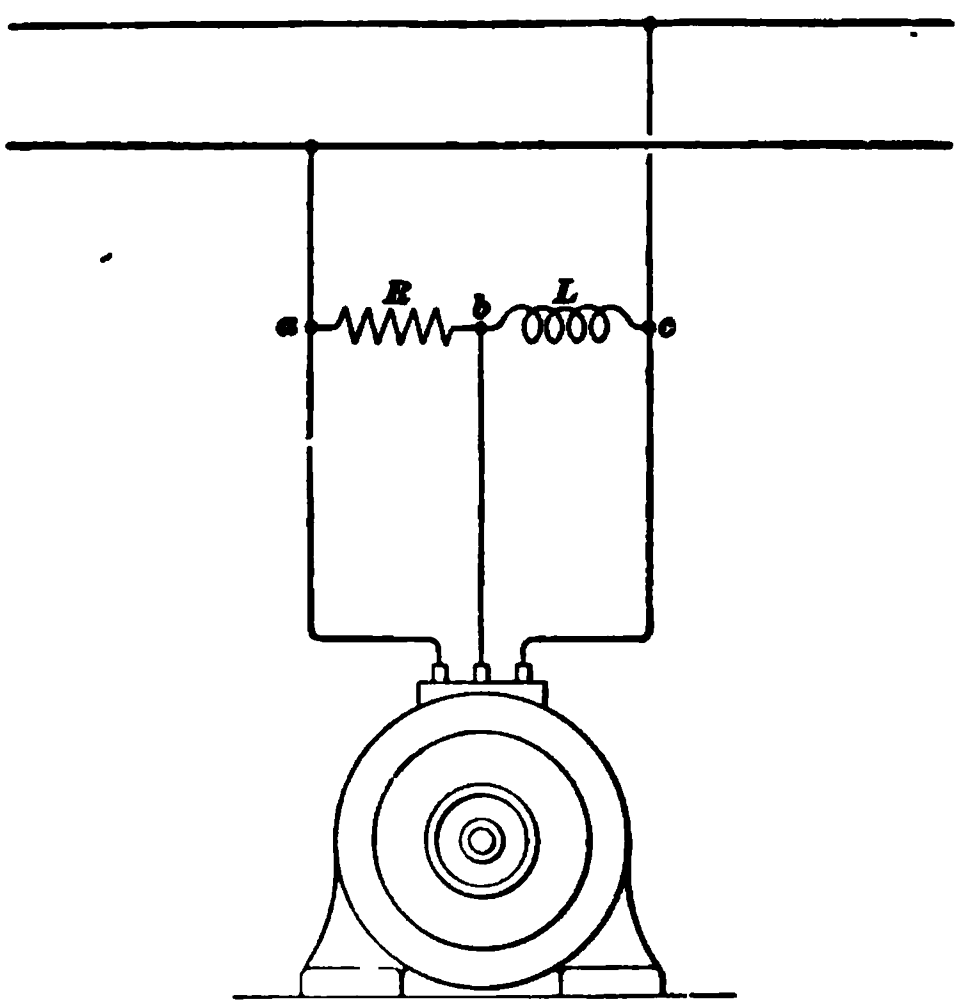


FIG. 35

lines. It is evident that the current in B will lag behind that in A, and if the resistance and inductance are correctly

proportioned the currents can be made to differ enough in phase to produce an imperfect form of rotating field sufficient to start the motor. The windings are frequently so designed that the necessary phase displacement is caused by the windings themselves, and outside resistance and inductance rendered unnecessary. In some cases one of the windings is a main, or working, winding, and the other is used only at starting, being cut out by open-circuiting it by means of a switch after the motor has attained its speed.

Fig. 35 shows another scheme for starting a motor on single-phase mains. Two of the terminals are connected to the mains, and the third terminal is connected to the point *b* between the resistance *R* and inductance *L*. The E. M. F. between *a* and *b* differs in phase from that between *b* and *c*, so that the different windings of the motor are supplied with displaced E. M. F.'s suitable for starting. A switch can easily be arranged to disconnect *R* and *L* after the motor has come up to speed, thus running it on the two outside lines only.

Fig. 36 shows a starting arrangement similar to Fig. 35, except that a condenser *C* is used instead of the inductance *L*. Sometimes where this combination is used, *R* and *C* are not cut out after the motor has attained speed, because the condenser *C* counteracts the self-induction of the motor and thus raises its power factor to such an extent that the small amount of loss in *R* is more than made up.

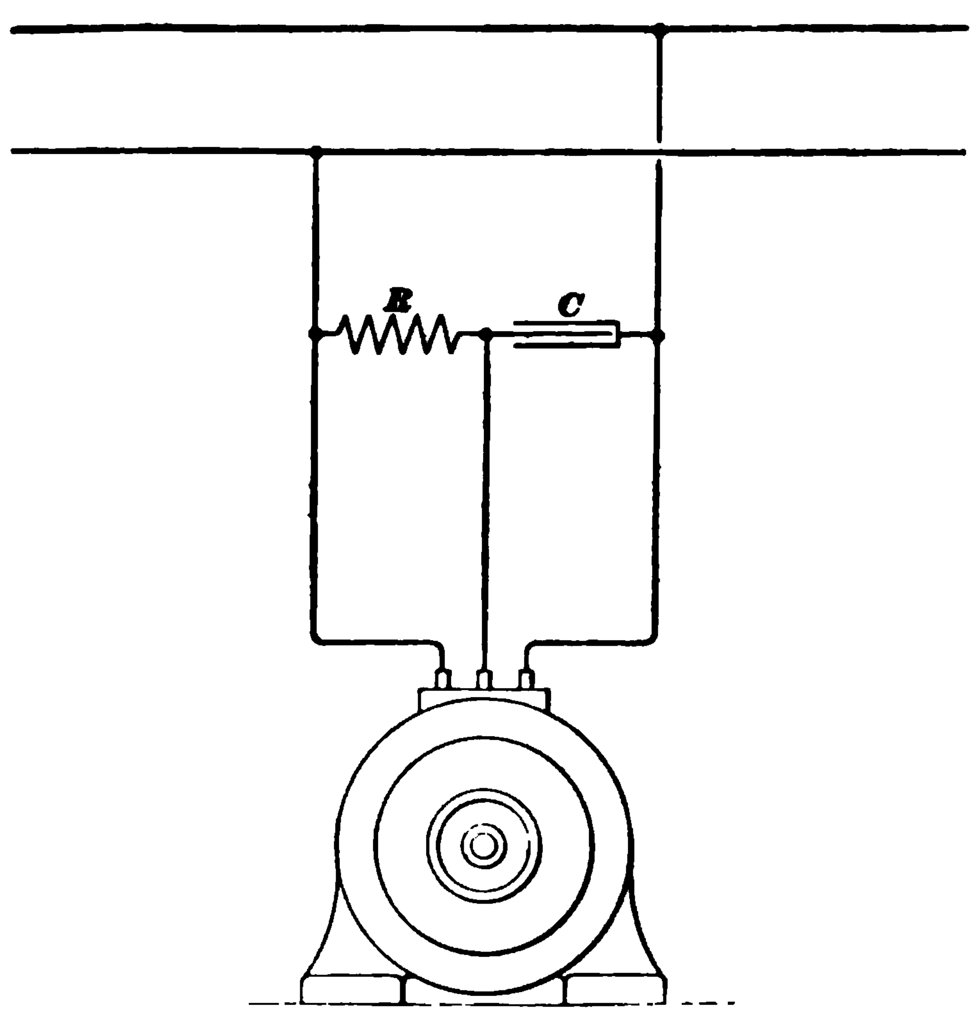


FIG. 36

57. It is thus seen that so far as construction is concerned, the single-phase induction motor is almost identical with the polyphase motor, the principal difference being in the method of starting and the way in which the revolving field is set up after the motor is in operation. Fig. 37 shows an interesting starting arrangement used very largely for small single-phase fan motors. Each pole piece A is provided with a magnetizing coil D in the usual manner; a slot c is made in the pole piece in which is placed a rectangular copper stamping B. In some cases this copper stamping is replaced by a number of turns of wire, the two ends of the coil being joined together so as to make a closed circuit. The

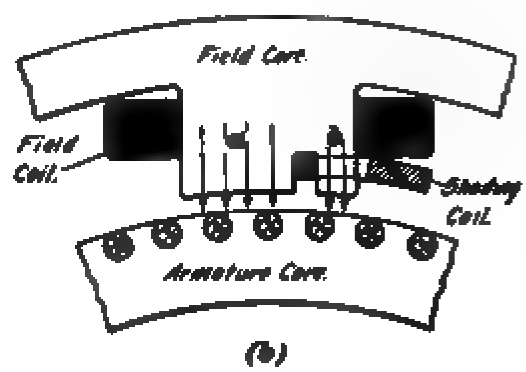


FIG. 37

field coil B sets up a magnetic flux a, and the flux b through the portion of the pole face covered by B is due to the combined effect of D and B. The flux passing through the copper stamping or shading coil, as it is often called, sets up induced currents that are out of phase with the flux; the effect of these induced currents is similar to that of a second set of coils with currents in them differing in phase from the current in the main field coils. In other words, the flux in one part of the pole face differs in phase from that in the other, thus producing the effect of a shifting field to a sufficient extent to bring the motor up to speed. The armature in these motors is a simple squirrel cage with round copper bars.

SERIES-MOTOR ON ALTERNATING CURRENT

58. If a motor constructed in every way like a series-wound direct-current machine be provided with laminated fields and supplied with current from alternating-current mains, it will start with a good torque and run up to speed under load, thus making a single-phase alternating-current motor. Since the field is in series with the armature, it follows that the current in each reverses at the same instant. It has already been shown in connection with direct-current motors that if the currents in both field and armature are reversed, the direction of rotation remains unchanged. Series motors, with laminated field, have heretofore been used very little on alternating current circuits because of the difficulty of making motors that would run without bad sparking at the commutator. Recently, however, much attention has been paid to the development of this type of motor with a view to its use for operating electric railways, and the design has been perfected so that motors of suitable size can now be built that will operate as well as series direct current motors of corresponding size. The series alternating-current motor has the same characteristics as the corresponding direct-current machine; i. e. the speed increases with decrease in load, and at the same time the torque decreases. Large torque at starting can be obtained and the motor is thus particularly suited to railway work. The frequency on which these motors are operated must be low (25 cycles or under), and as a frequency of 25 has become standard in railway work, most of them have been designed for that frequency. One advantage of the motor is that it will operate on either direct or alternating current. On account of its variable speed it is not well adapted for most stationary work.

SHUNT MOTOR ON ALTERNATING CURRENT

59. A machine constructed in the same way as a direct-current shunt-wound motor, but provided with a laminated field, will not operate well on alternating current. This is

because the shunt field has a very high inductance, and the current in it lags nearly one-quarter of a cycle behind the E. M. F. It is thus very much out of phase with the armature current, and but little power is delivered at the pulley. Such a motor would have a very low power factor, and while its performance might be improved by using a condenser in connection with the field, it is a type that has never come into use in competition with the single-phase induction motor.

REPULSION MOTOR

60. Fig. 38 illustrates the principle of a type of single-phase alternating-current motor known as a **repulsion motor.** The laminated field *A A* is excited by single-phase current. *C* is an armature provided with an ordinary direct-current winding connected to a commutator; *d* and *e* are thick brushes with their center line at an angle of about 45° with the center line of the poles. Suppose for the present that the brushes are not in contact with the commutator. When the field is excited, opposing E. M. F.'s will be induced in the two sides of the ring, like in a direct-current armature, and no current will be set up in the windings; no turning effort will be exerted, and the armature will not start. If a coil at *g* were short-circuited by means of a brush, no current would be set up in it because the plane of

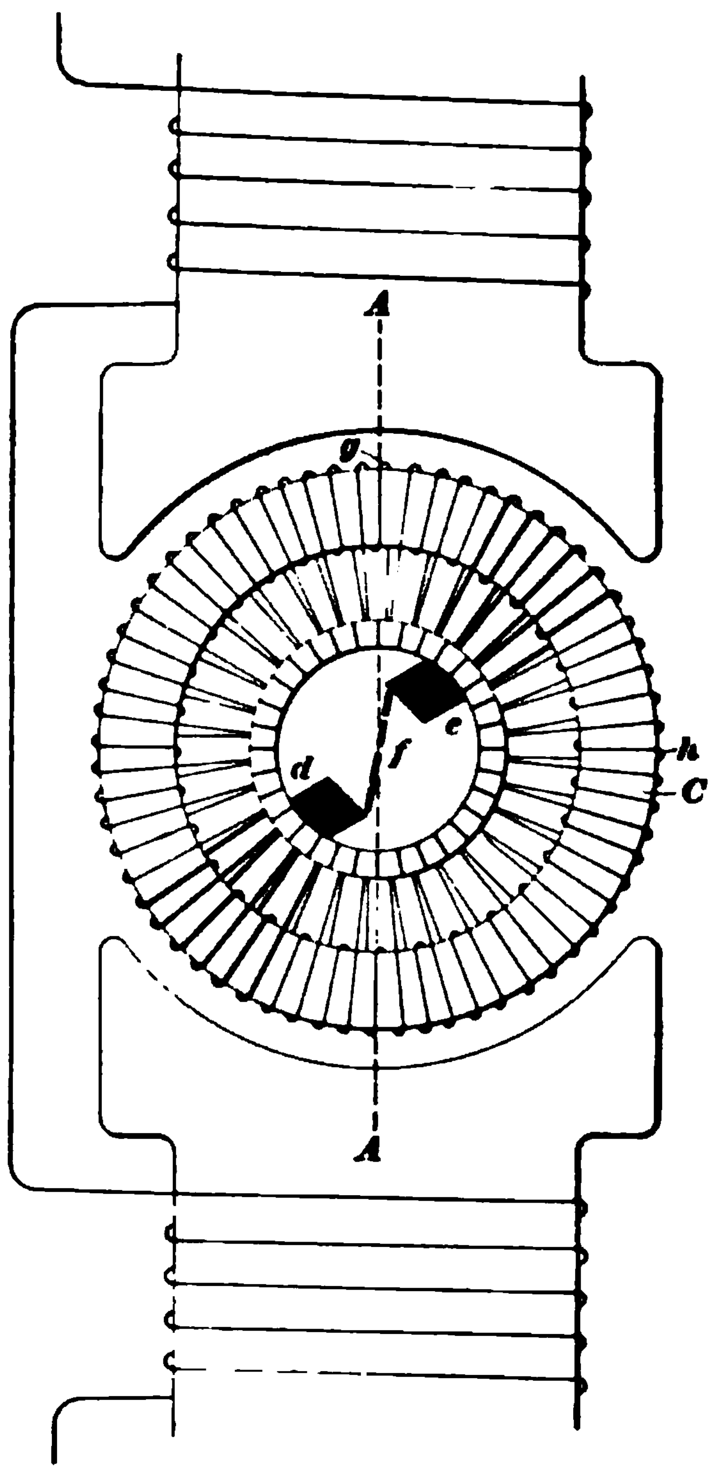


FIG. 38

this coil is in the same plane as that of the field; consequently, no torque would be exerted on the coil. If coil *h* were short-circuited, a heavy current would be set up in it because the alternating flux threads through it. However, there is no field, from the pole pieces, at *h* to react on the induced current; hence, no torque will be produced. On the coils located between *h* and *g* a varying torque would be exerted, the maximum occurring in those coils situated about half way between the two extremes. If, therefore, two thick brushes *d*, *e* are arranged so as to short-circuit a number of the coils lying in this region, a repulsive force will be exerted on the coils so short-circuited, and the armature will revolve. In Fig. 38 the short-circuited coils are shown by the heavy lines. It will be noted that only those coils that are short-circuited by the brush are effective in producing rotation, so that comparatively few of the armature coils are utilized. More coils can be utilized and the repulsive effect made stronger by connecting the brushes together, as shown by the heavy dotted connection *f*. The repulsion motor is a special type of single-phase induction motor, because the currents in the armature are set up by the inductive action of the field and are not supplied from an outside source.

WAGNER SINGLE-PHASE INDUCTION MOTOR

61. The Wagner single-phase induction motor has found extensive application because it gives a good starting effort with moderate current, and, while operating on single-phase circuits, compares favorably with polyphase induction motors. The general appearance of the motor is shown in Fig. 39. Fig. 40 is a sectional view showing the construction of the machine, particularly that part used when starting. The machine starts up as a repulsion motor, but after it has attained speed it operates as a regular single-phase induction motor with short-circuited armature. The field *A*, Fig. 40, is provided with a simple

single-phase winding distributed in slots. The armature is provided with a regular direct-current winding placed in slots and connected to a commutator Fig. 41. This commutator is of the radial type and brushes are arranged to press against it, as shown. In Fig. 41 one complete element of the armature winding is shown, the field being wound for four poles. In this case a wave winding is represented so that two brushes only are required for a

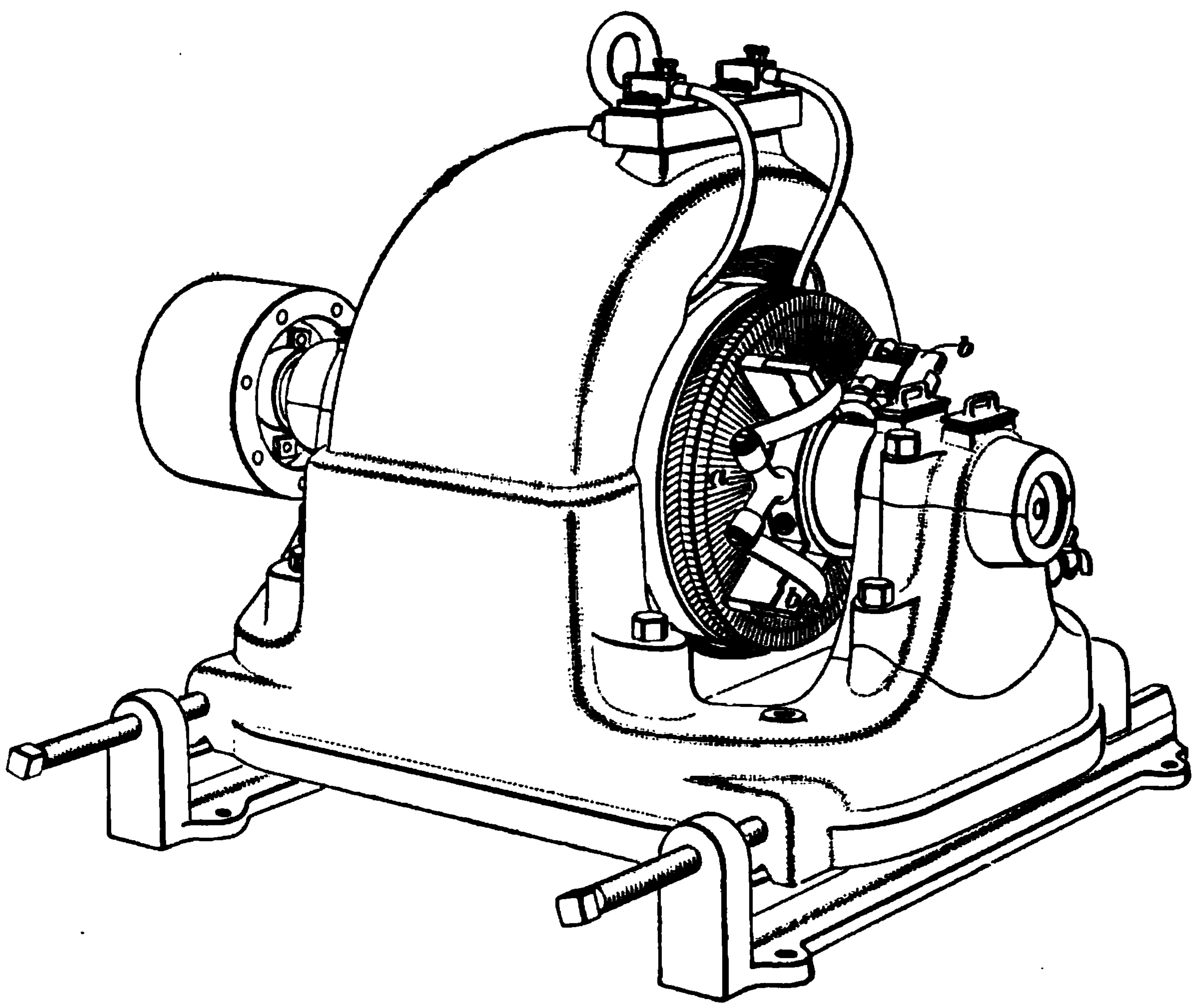


FIG. 39

four-pole machine. The brushes are connected together as shown, so that when current is sent through the field, the motor can start up because of the repulsive action on the armature coils, as previously explained. When the motor has attained full speed, the commutator is short-circuited by means of a ring that connects all the segments together and at the same time the brushes are lifted from the commutator, thus preventing brush friction

and wear except during the time that the commutator is actually in use.

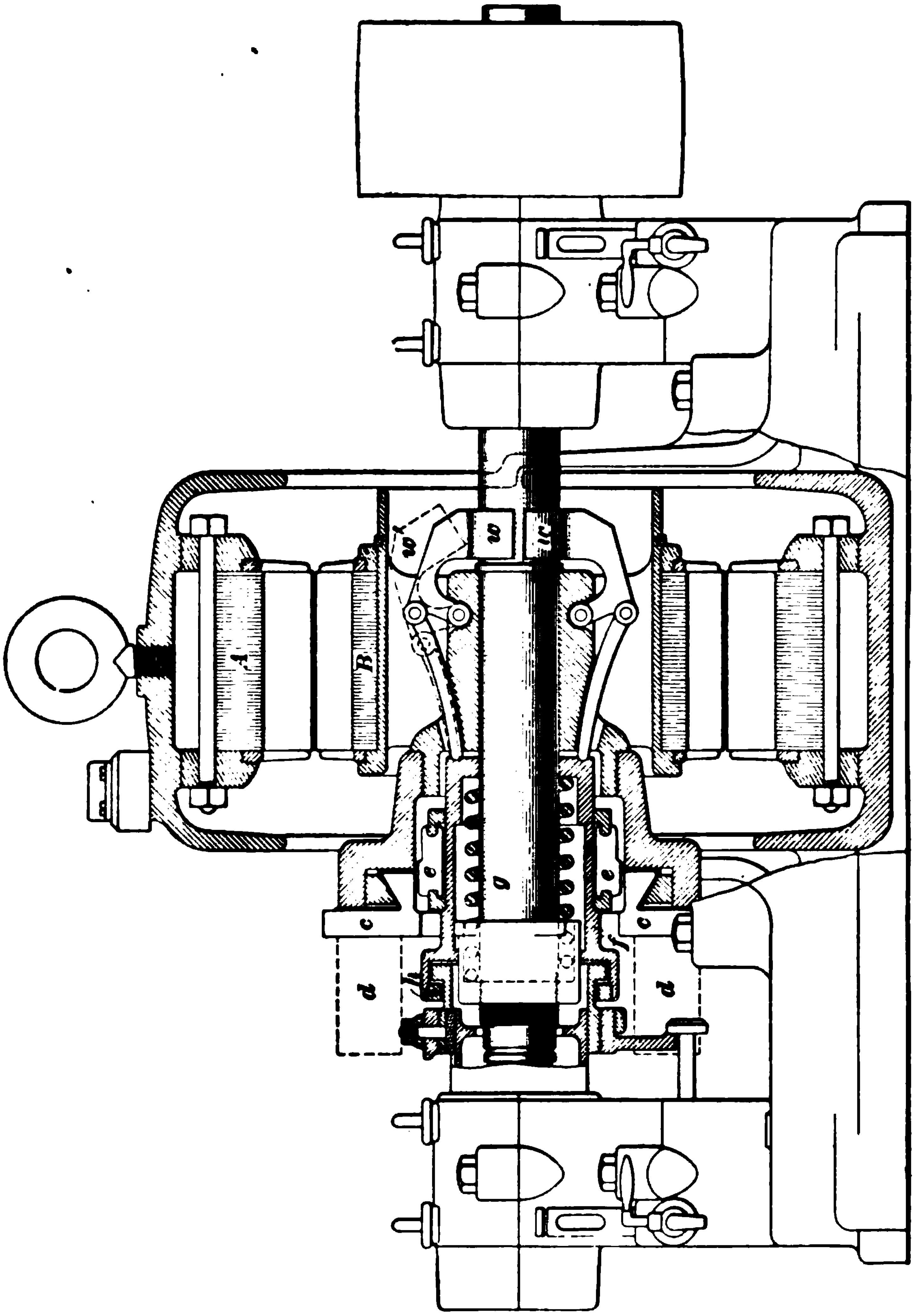


Fig. 40

The method of starting will be understood by referring to the sectional view, Fig. 40. The field laminations *A* are

held in a cast-iron frame designed to protect the windings as much as possible. The armature windings are carried in slots in the core *B*, and these windings are attached to the bars *c* of the radial commutator. The brushes, represented by the outlines *d*, *d* press on these bars when the motor is at rest or running below full speed. The continuous ring that short-circuits the commutator is shown at *e*, *e*;

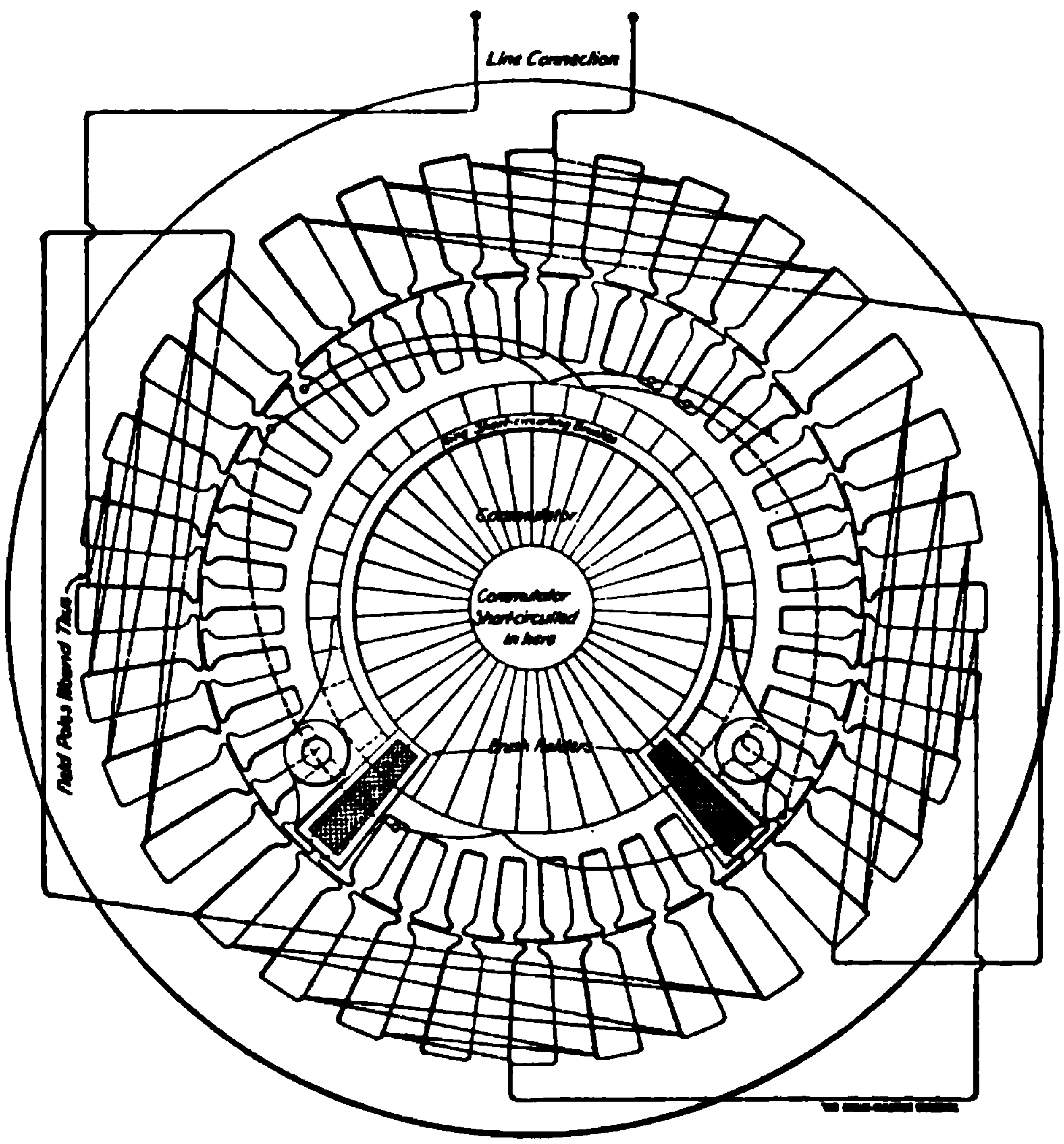


FIG. 41

this ring is mounted on the sliding sleeve *f*, the movements of which are controlled by the spring *g* and the weights *w*, *w*. When the motor attains full speed, the weights fly out on account of centrifugal force, and take up the position shown by *w'*. This movement forces sleeve *f* along the shaft and

brings c in contact with the commutator bars; at the same time the projection h pushes the brush-holder yoke to the left, and thus raises the brushes from the commutator. When the machine is shut down, the weights drop back and the spring g forces the collar to the right, thus removing the short-circuiting ring and bringing the brushes into contact with the commutator ready for the next start.

62. Fig. 42 shows characteristic curves of a 15 H. P. motor. It will be noticed that at full load the power factor

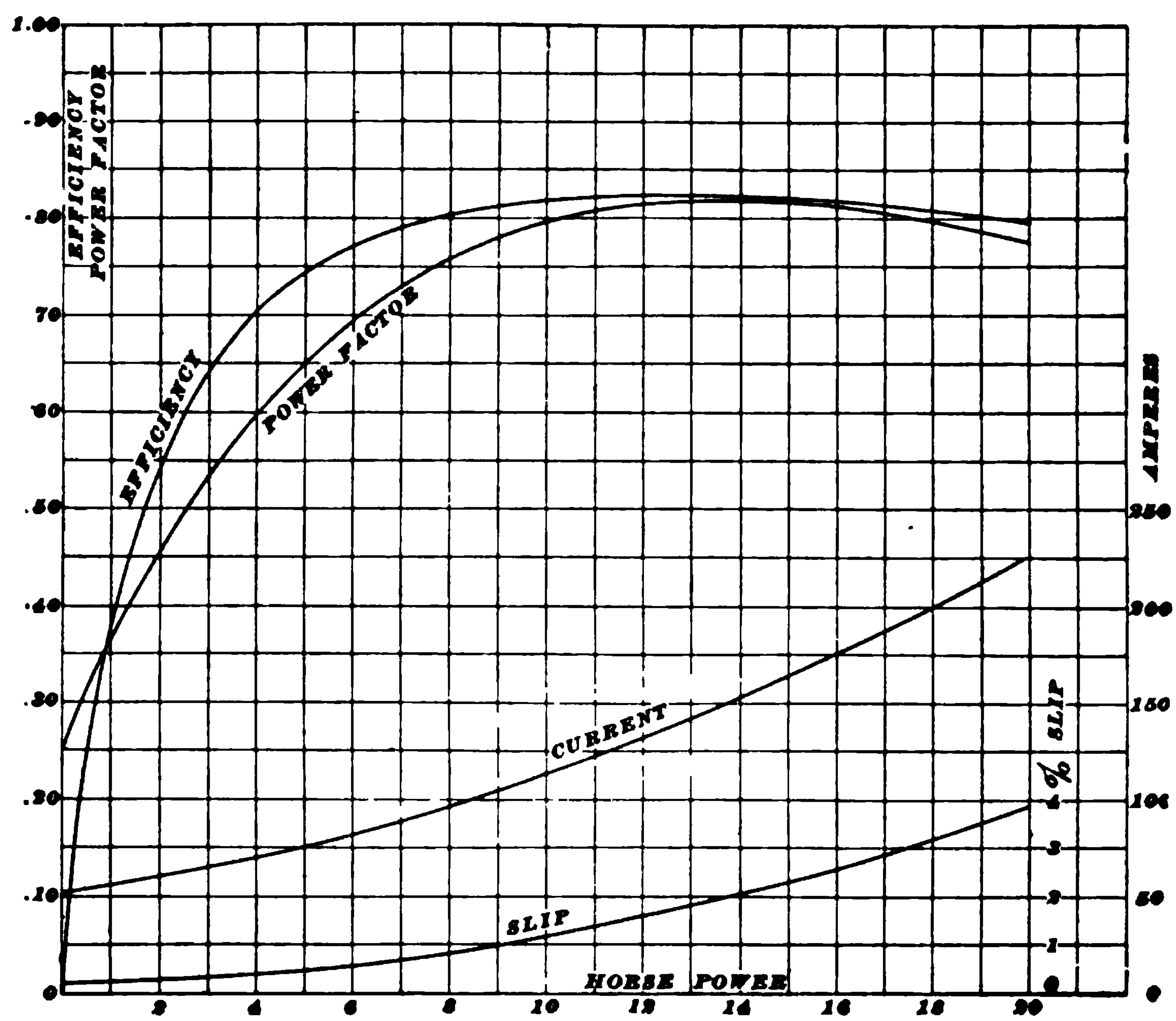


FIG. 42

is 82 per cent., and the slip less than 2.5 per cent. This compares quite favorably with polyphase induction motors of corresponding output.

ROTARY CONVERTERS

63. It is often necessary to change direct current to alternating, and vice versa, and machines for accomplishing this are known as **rotary converters**, or **rotary transformers**. These machines are also frequently referred to as **synchronous converters**, for reasons that will appear later. The transformation might be effected by having an alternating-current motor coupled to a direct-current generator, simply using the alternating current to drive the generator. An arrangement of two machines is, however, not usually necessary, although such motor-generator sets are used to some extent. Rotary converters are largely used for changing alternating current to direct for the operation of street railways, electrolytic plants, etc.

SINGLE-PHASE CONVERTERS

64. Suppose an ordinary Gramme ring armature to be

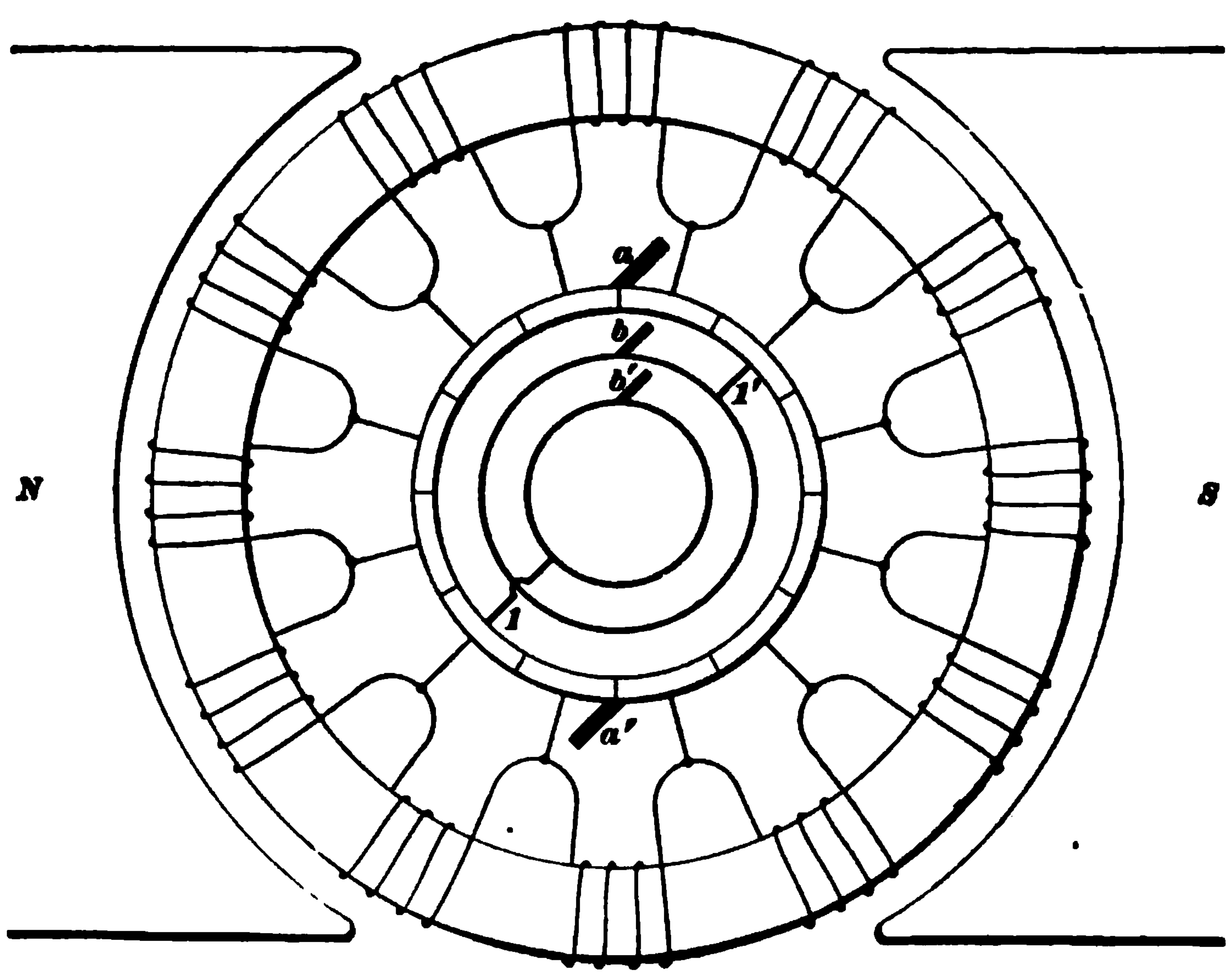


FIG. 43

revolved in a two-pole field, as shown in Fig. 43; a direct

current will be obtained by attaching a circuit to the brushes *a*, *a'*. If, instead of the commutator, two collector rings were attached to opposite points of the winding, an alternating current would be obtained in a circuit connected to *b*, *b'*. If the machine be equipped with both commutator and collector rings, the armature may be revolved by means of direct current led in at the brushes *a*, *a'*, thus running it as a motor instead of driving it by a belt. The conductors on the revolving armature will be cutting lines of force just as much as they were when the machine was driven by a belt; therefore, an alternating current will be obtained from the rings *b*, *b'*. In other words, the machine acts as a converter, changing the direct current into a single-phase alternating current. If the operation be reversed and the machine be run as a synchronous alternating-current motor, the alternating current will be transformed to direct.

65. In the above single-phase rotary converter, it is evident that the maximum value of the alternating E. M. F. occurs when the points *1*, *1'*, to which the rings are connected, are directly under the brushes *a*, *a'*; that is, the maximum value of the alternating E. M. F. is equal to the continuous E. M. F. For example, if the continuous E. M. F. were 100 volts, the effective volts on the alternating-current side would be $\frac{100}{\sqrt{2}} = 70.7$ volts. Therefore, if E is the alternating voltage and V the direct, we may write for a single-phase rotary converter,

$$E = .707\ V \qquad (7)$$

TWO-PHASE CONVERTERS

66. By connecting four equidistant points of the winding *b*, *c*, *d*, and *e*, Fig. 44, to four collector rings, we would have a two-pole two-phase, or quarter-phase, converter. In

this case we would have two pairs of lines leading from the

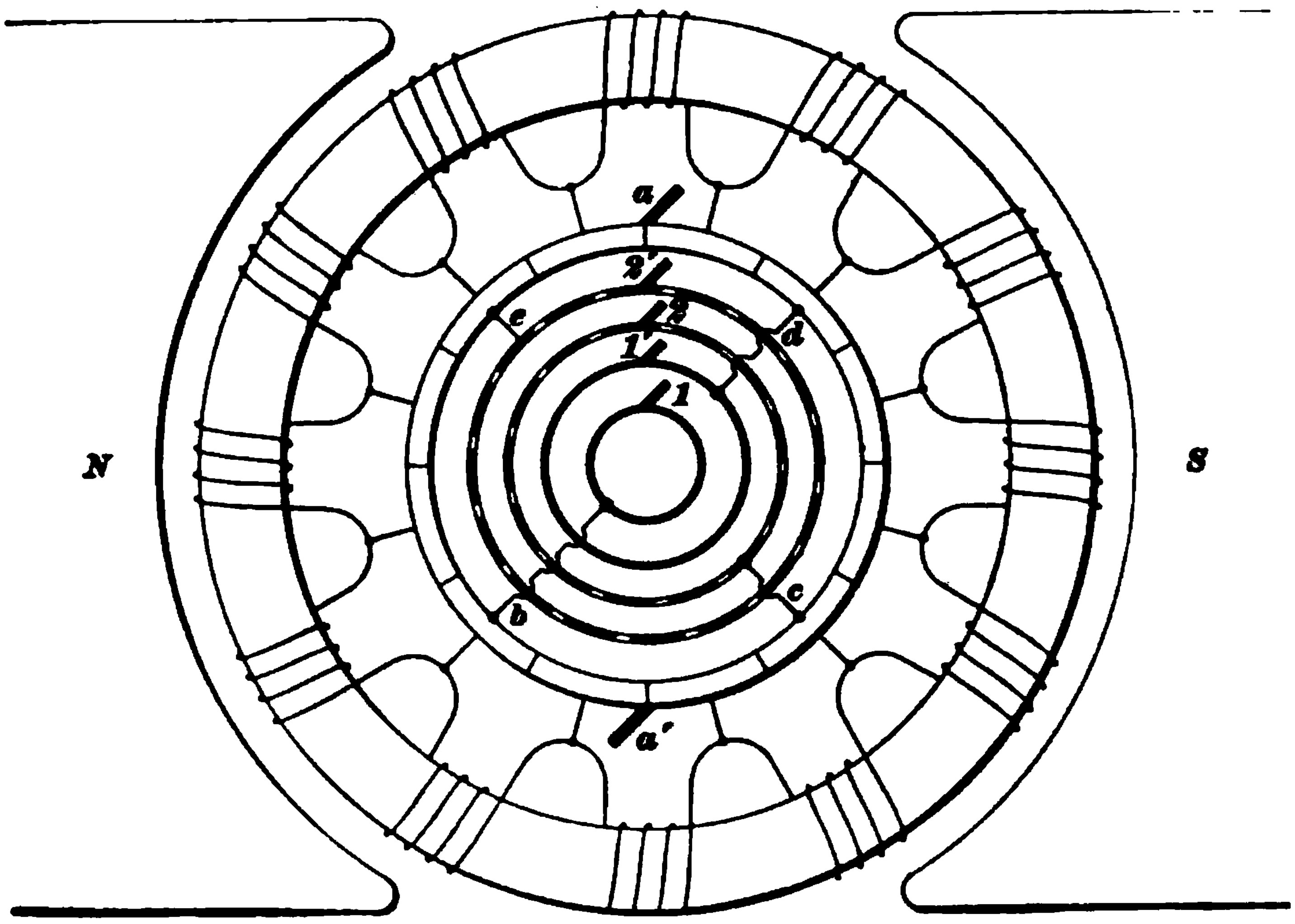


FIG. 44

brushes *1*, *1'*, *2*, *2'*. The E. M. F. between *1* and *1'* or between *2* and *2'* would be given by formula **7**.

THREE-PHASE CONVERTERS

67. By connecting three equidistant points as shown at *b*, *c*, and *d*, Fig. 45, a three-phase converter is obtained. Since all direct-current armatures have closed-circuit windings, it follows that the connections on the alternating-current side of a three-phase rotary converter are always Δ, the Y connection not being possible. If E be the effective voltage between the lines on the alternating side of a three-phase rotary converter and V the voltage of the direct-current side,

$$E = .612\ V \qquad \textbf{(8)}$$

If such a converter were supplied with direct current at 100 volts pressure, alternating current at 61.2 volts would be

obtained; and if it were desired to obtain 100 volts direct

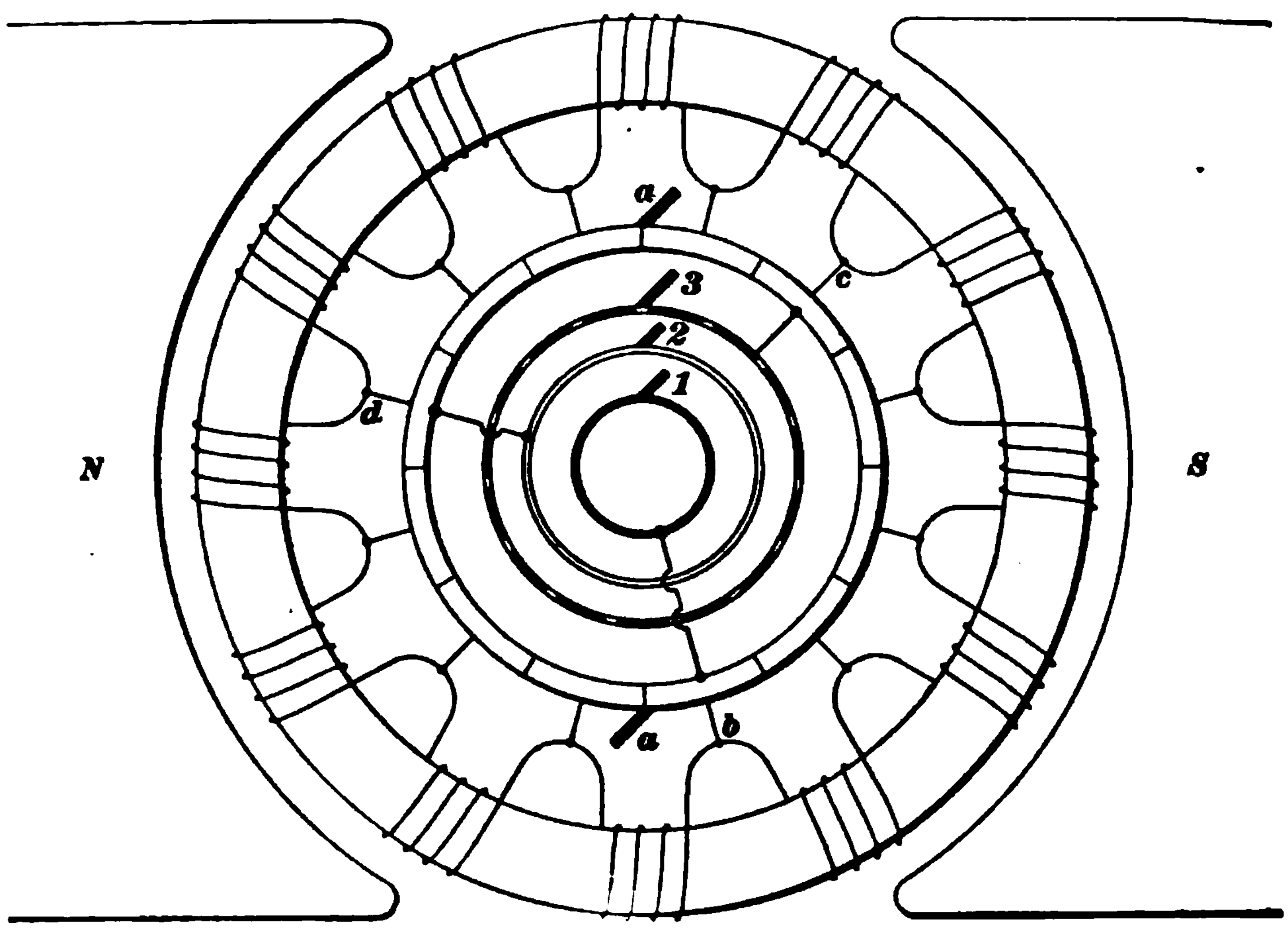


FIG. 45

current from alternating, the alternating side would have to be supplied at a pressure of 61.2 volts.

The proof of the above relation is as follows:

Suppose the closed-circuit winding of a two-pole rotary transformer is represented in Fig. 46.

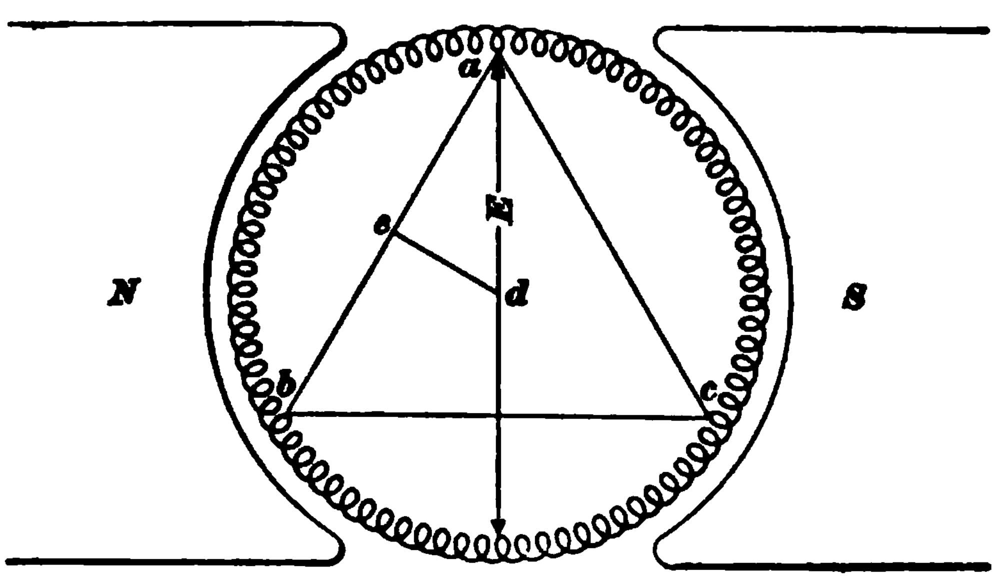


FIG. 46

The E. M. F. V obtained across the diameter of the winding would be the continuous E. M. F. of the machine. It

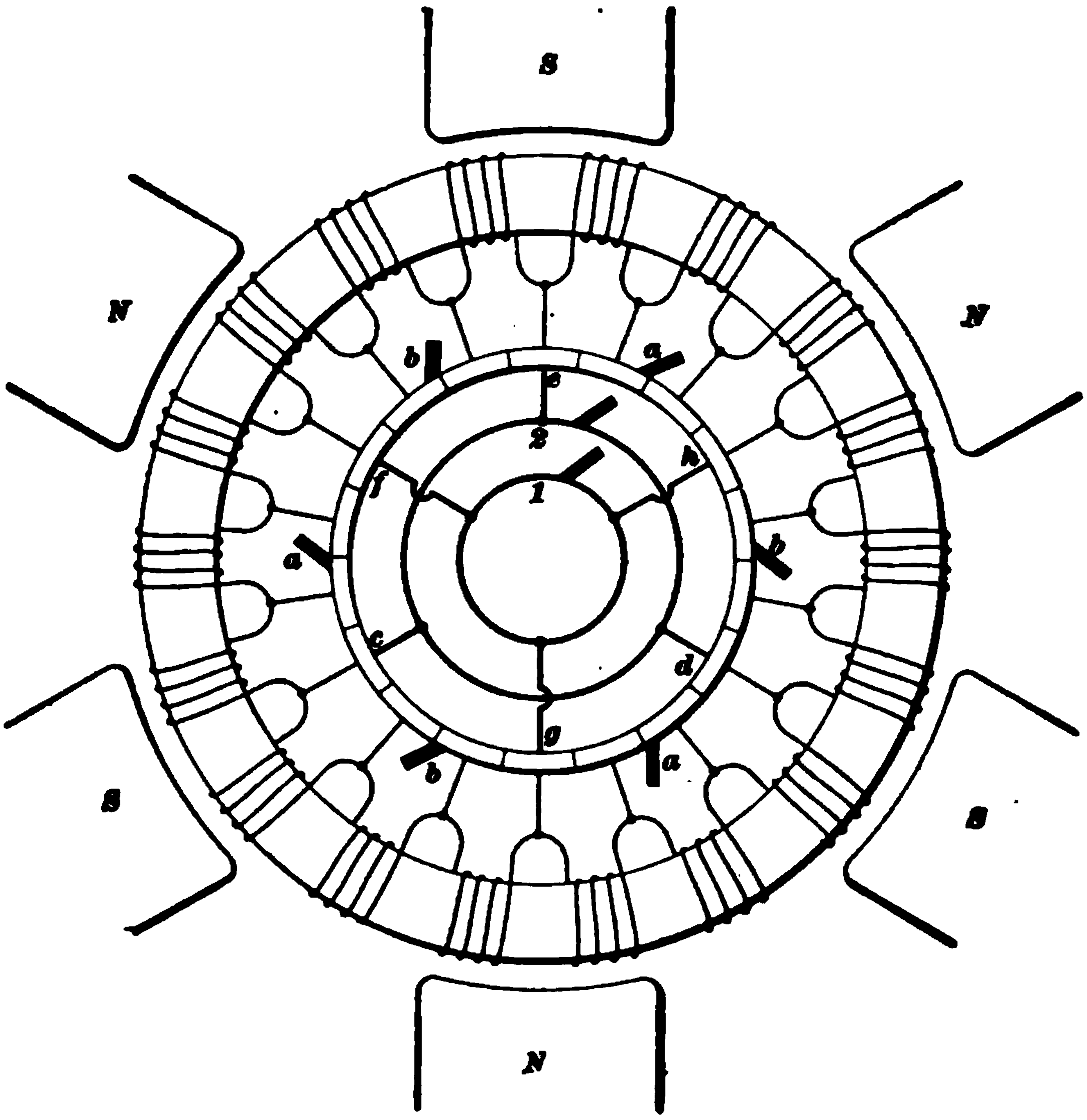


Fig. 47

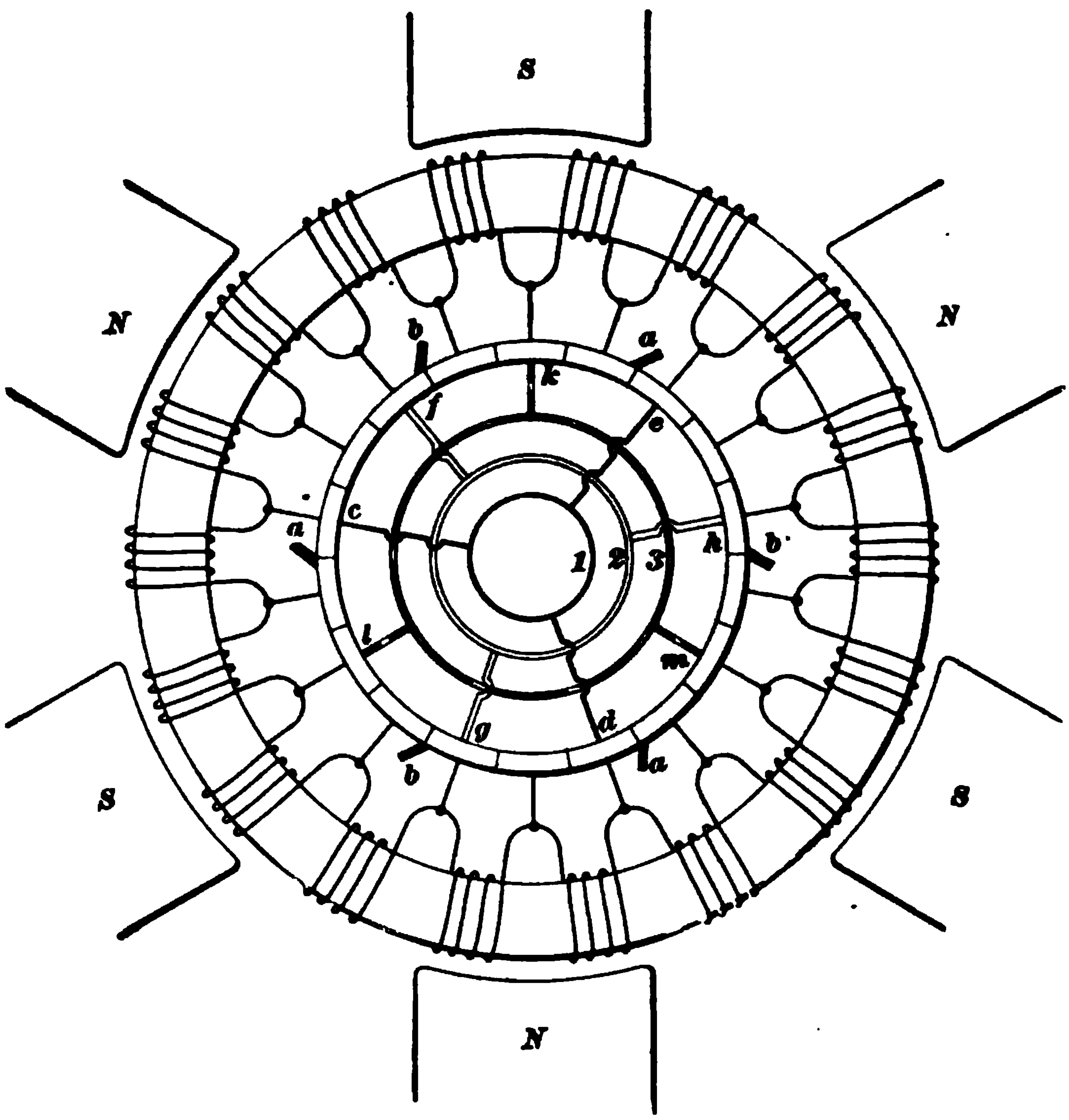


Fig. 48

would also be the maximum alternating E. M. F. for a single-phase rotary transformer. For a three-phase rotary, the winding would be tapped at three equidistant points, *a*, *b*, and *c*, and the maximum values of the alternating E. M. F. between the three collector rings would be represented by the three lines *a b*, *b c*, and *c a*. To obtain the value of this E. M. F. in terms of the continuous E. M. F., from the center *d* draw the line *d e* perpendicular to *a b*.

Then the angle $a\,d\,e = 60°$.

$$a\,e = \tfrac{1}{2}\,V \sin 60°$$
$$a\,b = 2\,a\,e = V \sin 60°$$

$a\,b$ = maximum E. M. F. of alternating-current side of machine. Then, the

$$\text{effective E. M. F. } E = .707\,V \sin 60° = .707 \times .866 \times V = .612\,V$$

MULTIPOLAR ROTARY CONVERTERS

68. The windings shown in Figs. 43, 44, and 45 show the connections for two-pole machines; but rotary transformers are nearly always made multipolar in order to reduce the speed of rotation. In the single-phase machine shown in Fig. 43, it was necessary to have only one connection to each ring; in a multipolar machine it is necessary to have as many connections to each ring as there are pairs of poles on the machine. Fig. 47 shows the connections for a six-pole single-phase converter. Here the ring *1* is connected to the points *g*, *h*, and *f*, while ring *2* is connected at *c*, *d*, and *e*, these points being the equivalent of 180° apart. If only two connections were made, as in Fig. 43, the whole winding would not be utilized. Fig. 48 represents the same armature connected up as a three-phase converter. Here each of the three rings has three connections, as before, and these connections are the equivalent of 120° apart. For example, the angular distance from *k* to *e* is one-third the distance from

north pole to north pole, which represents 360°. Such a winding would, therefore, have the three connections *c*, *d*, *e* for ring *1*; *f*, *g*, *h* for ring *2*; and *k*, *l*, *m* for ring *3*, there being as many connections for each ring as there are pairs of poles.

69. Fig. 49 shows the general appearance of a three-phase rotary converter. The three collector rings are

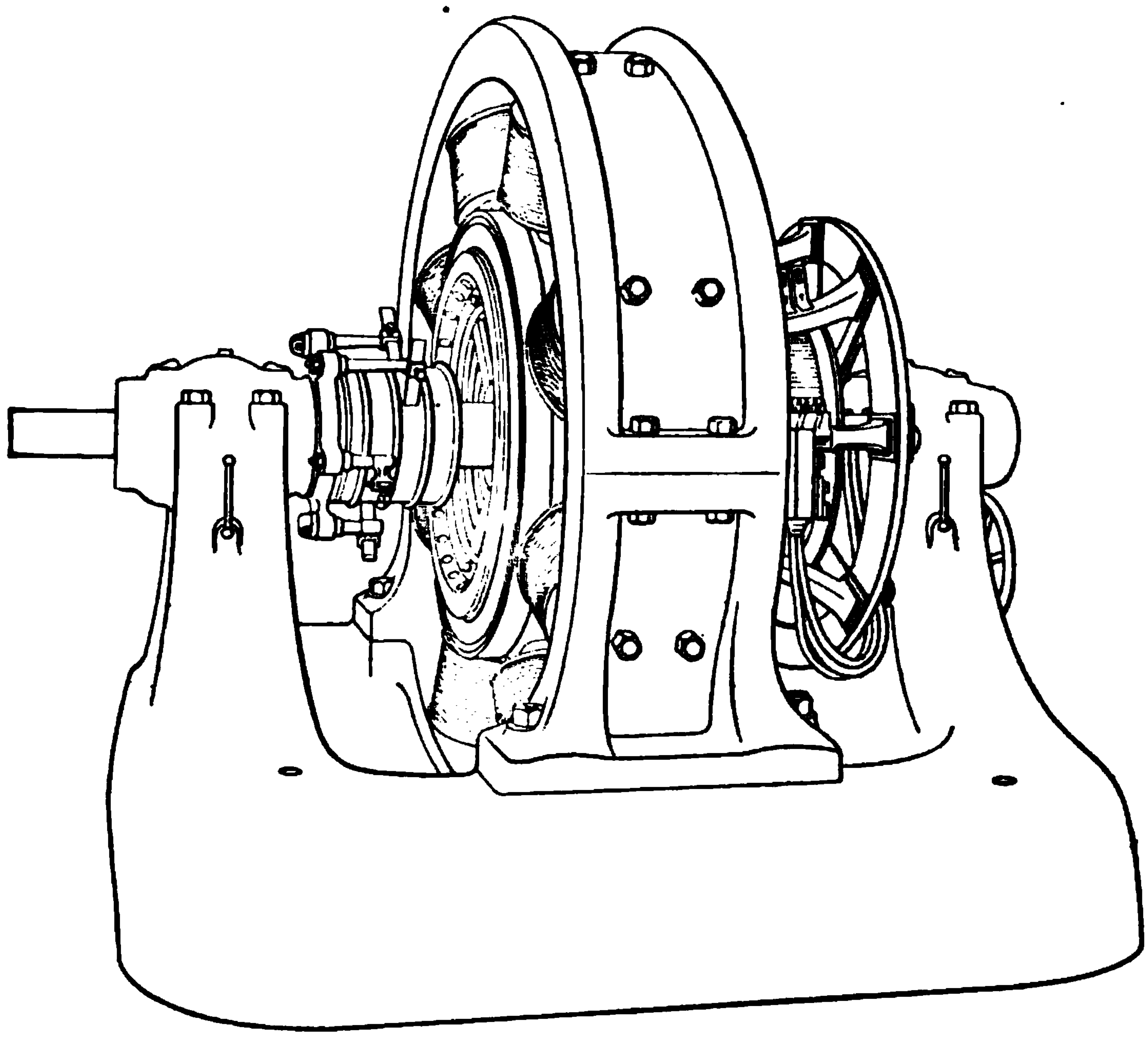


FIG. 49

seen at the left-hand end of the machine, and the commutator is shown at the right. Like alternators, rotary converters are built for a large range of output and frequency.

In the foregoing explanations regarding the rotary converter, simple ring windings have been used, because of the ease in following the connections. In converters as actually built, the windings are of the toothed-drum type and in fact are the same as used on direct-current multipolar

dynamos. Either series- or parallel-wound drums may be used. With a series-wound drum, only one connection to each collector ring is necessary, no matter how many poles the machine may have. With a parallel-wound drum, there would be a connection to each ring for each pair of poles, as shown for the ring windings given in the preceding article.

OPERATION OF ROTARY CONVERTERS

70. Rotary converters are used to change alternating current to direct current in the great majority of cases. They are used comparatively seldom to change direct-current to alternating, though special cases sometimes arise where it is advantageous to use them in this way. When used to change direct current to alternating, they are frequently called **inverted rotaries**, though there seems to be little need for this special name, because the machine itself is in nowise different; the only difference is in the manner in which it is used.

A rotary converter, run in the ordinary way from alternating-current mains, operates as a synchronous motor, and hence runs at a constant speed. Its speed will not vary, no matter what load may be taken from the direct-current side, provided the speed of the alternator that supplies the current is maintained at a constant value.

71. Heating of Rotary Converters.—While the rotary converter behaves on the one hand like a synchronous motor and on the other like a direct-current dynamo, it has a number of peculiarities due to the combination of these two in a single piece of apparatus. One of the chief differences is in the heating effect. If a rotary converter is run as a direct-current dynamo, the output that can be obtained from it is considerably less than if it is run as a converter; that is, with the same heating effect in the armature, a given machine is capable of a greater output when run as a converter than when operated as a direct-current dynamo.

This is not true of the single-phase converter, but these are seldom if ever used in practice. The reason that a multiphase converter gives a greater output than a direct-current dynamo of the same size may be explained in a general way as follows.

72. The currents that actually flow in the armature conductors are of peculiar character. They are the difference between the alternating current supplied and the direct current given out. For example, take the simple

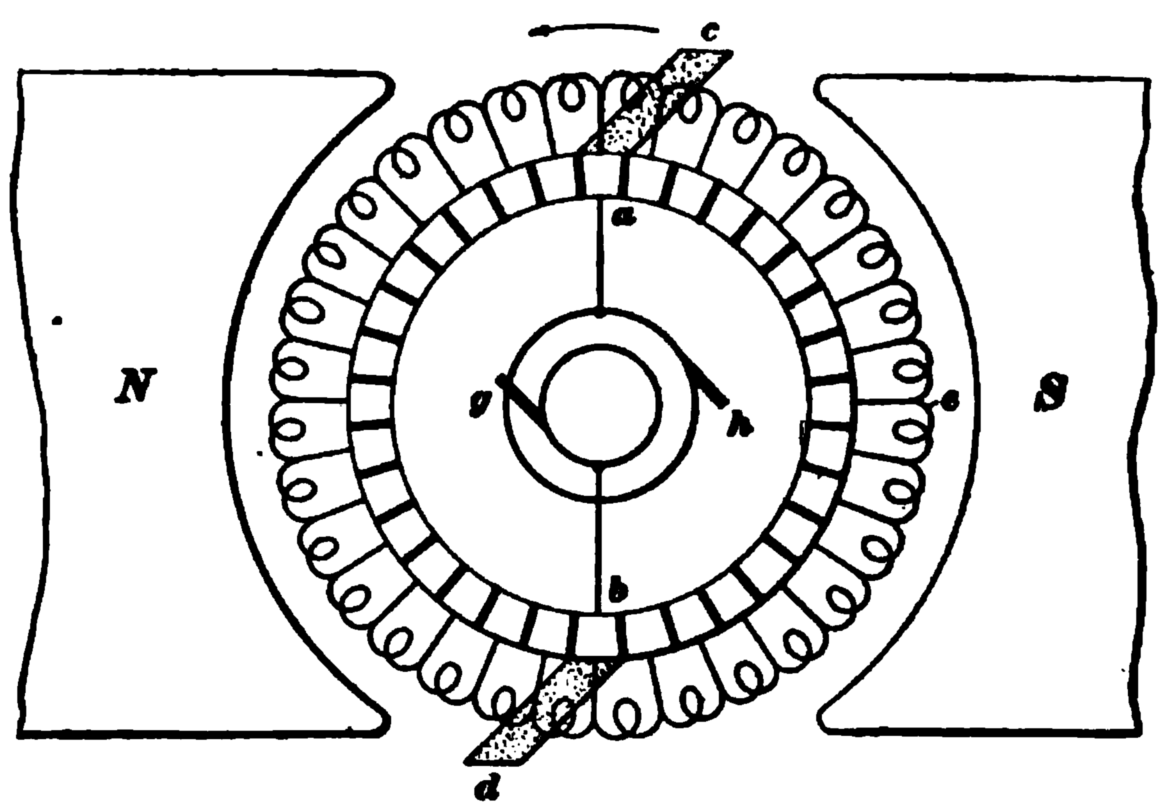


FIG. 50

case of the single-phase converter shown in Fig. 50, where the various coils are shown connected to the commutator; *c* and *d* are the brushes from which direct current is delivered, and *g*, *h* the brushes through which alternating current is supplied. At the instant a coil passes under *c* or *d* the direct current in it is reversed, but while it is turning through the half revolution between *c* and *d* the direct current remains at a constant value. Take the coil *e*, for example, this being the coil situated midway between the taps *a*, *b* and the brushes *c*, *d*. The direct current in this coil may be represented by the flat-topped wave *a–b–c–d–e*, etc., Fig. 51 (*a*). The alternating current in the half of the armature from *a* around to *b*, including coil *e*, will be a

maximum when the armature is in the position shown, and will have become zero when coil *e* comes under brush *c*. In other words, the alternating current in coil *e* will reverse at the same instant as the direct current, and hence may be represented by the wave *m–n–o–p*, etc., which passes through zero at the same instant as the flat-topped wave. The

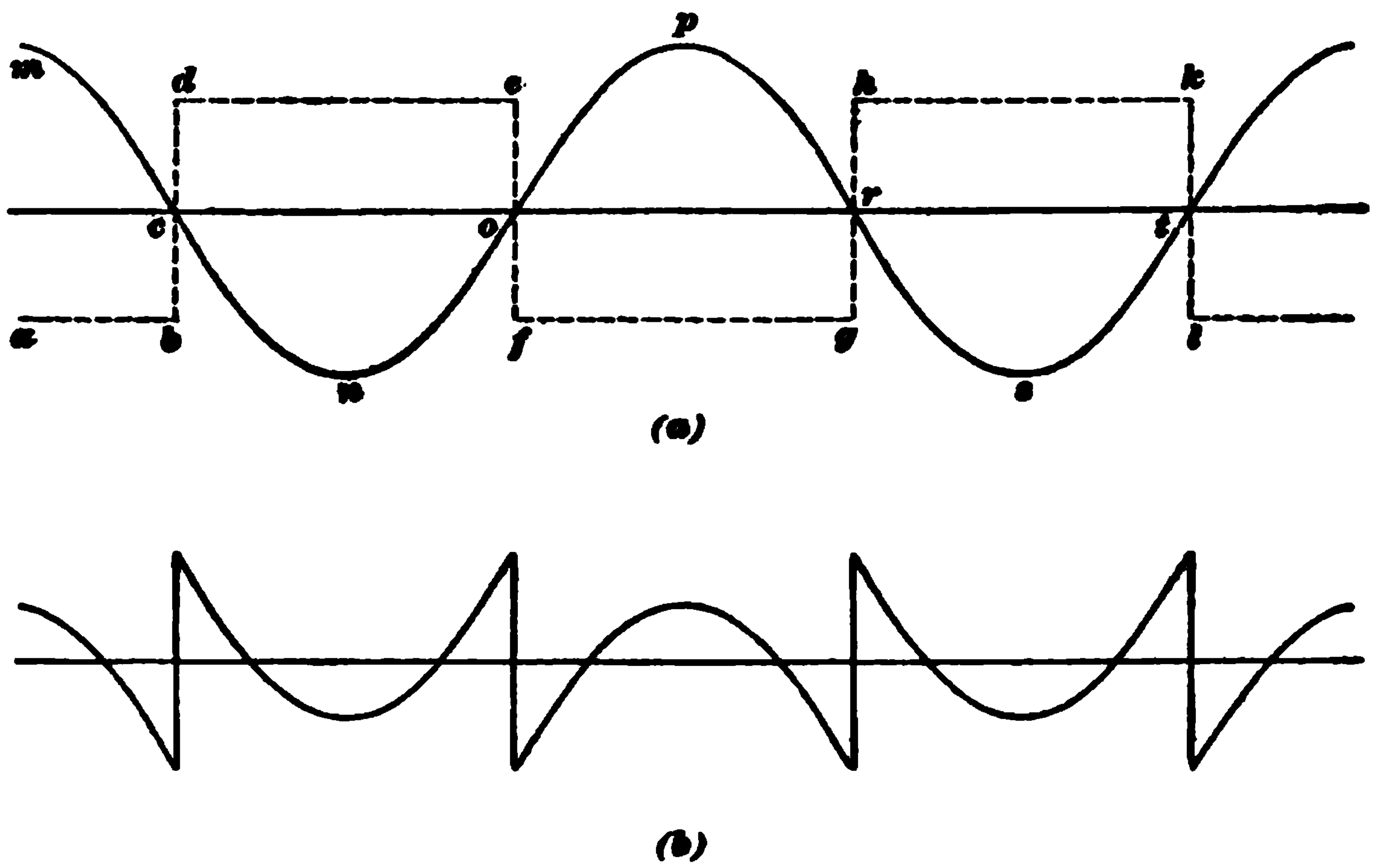


Fig. 51

alternating current and direct current flow in opposite directions, because in one case the machine acts as a dynamo and in the other as a motor.

The current that actually flows in the conductors is found by combining the two curves shown in (*a*), thus giving the resultant curve shown in (*b*). This peculiar wave represents the current in coil *e*; it is easily seen that the average value of the current is much smaller than that represented by the flat-topped wave in (*a*), which represents the current that would flow in the coil if the machine were used as a direct-current dynamo; hence, the heating will be less because the heating is proportional to the square of the effective value of the current.

73. It should be noted that the curves given in Fig. 51 represent the component and resultant currents in coil *e*

only. In the case of a coil situated on either side of *e*, the direct-current or flat-topped wave would not pass through zero at the same time as the alternating current, and the nearer the coil is to the tapping-in points, the greater difference in phase there would be between the two curves. The resultant current in each of the coils is therefore different, and a different heating effect is produced, the coils near the tapping points heating considerably more than the coils situated near *e*. As the number of tapping points and the number of phases is increased, the more uniform does the heating effect become, and the less also it becomes as compared with that produced when the machine is run as a direct-current generator. In a single-phase rotary the sum of the heating effects in all the coils is greater than if the machine were run as a direct-current dynamo, because the maximum value that the resultant current reaches in the coils near the tapping-in points is very much higher than the value of the direct current. The heating in these coils is therefore excessive, and brings up the total heating effect to an amount greater than that of the corresponding direct-current machine. As the number of phases is increased, and the angular distance between the tapping points decreased, the total heating effect is decreased, and for multiphase converters is considerably less than that of the corresponding direct-current machine.

74. This difference in the heating effect of a rotary converter as compared with a direct-current generator is important because it means that such a machine can be made smaller and lighter for the same output than a direct-current dynamo. A machine connected up for three phases will give a larger output than the same machine connected for single-phase operation, and a six-phase machine will give a still larger output with the same amount of heating. A six-phase machine is one in which the windings are tapped at six equidistant points and the terminals led to six collector rings. Such a machine would be supplied by six currents differing in phase by 60°; these currents are easily

obtained from a three-phase system by a special arrangement of transformers.

Six-phase converters are used to a considerable extent in practice because of the increased capacity obtained, but a larger number of phases has not been employed to any extent, because the gain in output is more than offset by the complexity caused by the increased number of collector rings, brushes, transformers, and transformer connections. If the output when used as a direct-current machine is taken as 1, then the output when run as a three-phase converter will be 1.34; as a quarter-phase, or four-phase, converter, 1.64; and as a six-phase converter, 1.96. In other words, the output as a three-phase converter is about one-third greater than as a direct-current machine, and the output as a six-phase converter is almost twice as great. The above figures assume that the armature current and E. M. F. are in phase. If there is a lag between the current and E. M. F., the output when operated as a converter is less than that represented by the above figures. Six-phase converters and the transformer connections used with them will be taken up later.

75. Voltage Regulation of Rotary Converters.—It has already been noted that the rotary converter, as ordinarily used, operates as a synchronous motor, and that the ratio of the alternating voltage to that on the direct-current side is a fixed quantity. For example, suppose it were desired to transform alternating current at 2,000 volts to direct current at 500 volts, suitable for operating a street railway. We will suppose that a three-phase rotary transformer is employed. Then it follows that the alternating current must be supplied to the machine at a pressure of $E = .612\ V = .612 \times 500 = 306$ volts. The alternating current would, therefore, be first sent through static transformers wound so as to reduce the pressure from 2,000 to 306 volts, and the secondary coils of these transformers would be connected to the alternating-current side of the converter.

If it is necessary to vary the direct E. M. F. through any considerable range, the alternating E. M. F. must be varied also. This is frequently accomplished by using transformers provided with a number of taps from the secondary windings, so that the turns can be cut in or out, thus varying the alternating E. M. F. applied to the rotary. Another plan is to insert potential regulators between the secondary of the transformers and the collector rings of the rotary. Both these methods of regulation will be described more fully in connection with the uses of rotary converters in power-transmission systems.

76. If the field excitation of a rotary converter is changed, the current taken by the machine can be made lead the E. M. F. or lag behind it, according as the field is strengthened or weakened from the amount corresponding to a power factor of unity. Converters are nearly always operated with a field excitation that will give a power factor as near unity as possible, because then, for a given load on the direct-current side, they take the minimum current from the line. Changes in the field magnetization will cause changes in the direct-current voltage through a limited range. Increasing the excitation makes the machine have the same effect as a condenser, and causes the voltage at the terminals to rise, thus increasing the direct E. M. F. Lowering the E. M. F. makes the current lag and lowers the applied E. M. F. The range of regulation that can be obtained by this method is, however, comparatively small, and besides, it has the disadvantage of decreasing the power factor, so that wherever any considerable range is desired the applied E. M. F. is varied, as described above.

77. Operation From Direct-Current Side.—When a rotary is supplied with direct current, it runs as a direct-current motor and its behavior under certain circumstances is quite different from that when it is operated from the alternating-current side. Weakening the field will cause the armature to speed up, and strengthening the field will

slow it down as with any direct-current motor. Altering the field strength will not change the alternating E. M. F., because every change in field strength is accompanied by a change in speed, and the alternating E. M. F. that is generated in the conductors remains the same. In order to vary the alternating E. M. F. it is necessary to vary the direct E. M. F. applied to the armature, or else use potential regulators in the lines leading from the alternating side of the rotary; the latter would in most cases be the more practicable method.

There is a peculiar effect sometimes met with when rotaries are operated with direct current. If the alternating-current side is accidentally short-circuited, the machine is apt to race, because the heavy lagging current set up in the armature exerts a powerful demagnetizing action on the field and weakens it to such an extent that the machine attains a high speed.

DOUBLE-CURRENT GENERATORS

78. If a machine constructed in the same way as a rotary converter be driven from some outside source of power, it will deliver direct current from the commutator end and alternating current from the collector rings. A machine so operated is called a *double-current generator*. The full output of the machine may be delivered as direct current, as alternating current, or partly as one and partly as the other, provided, of course, that the combined output on the two sides does not exceed the capacity of the machine.

Double-current generators are useful where it is desired to have part of the output of a plant as direct current for utilization near at hand, and part as alternating current for transmission to distant points.

While the construction of a double-current generator is similar to that of a rotary converter, the heating action in the armature is quite different. In the rotary converter, we have just seen that the current in the armature conductors is the difference between the current taken as a motor and

the current delivered as a dynamo. In the double-current generator, the action is that of a generator on both sides, and the currents in the armature conductors are the sum of the currents delivered to the two sides. The heating is, therefore, considerably greater than if the same machine were used as a rotary converter delivering an equal output. Another point of difference in the action of the two machines lies in the effect of armature reaction. In a polyphase rotary converter, the armature reaction due to the direct current is offset by that due to the alternating current flowing in the opposite direction. In the double-current generator both currents react on the field and produce the same effects as the armature reaction in a direct-current generator. In case a heavy inductive load be thrown on the alternating-current side, the lagging current produces a powerful demagnetizing action on the field. This would greatly affect the voltage if the machine were self-exciting, as with ordinary direct-current machines, and in order to secure a stable field, double-current machines are generally separately excited. In most cases they are also provided with a series-field winding, through which the direct current passes and strengthens the field as the load increases.

INDEX

NOTE.—All items in this index refer first to the section and then to the page of the section. Thus "Alternation 16 4" means that alternation will be found on page 4 of section 16.

E